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Ethnomedical specialists and their supernatural theories of disease

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Abstract

"Religious" healing specialists such as shamans often use magic. Evolutionary theories that seek to explain why laypersons find these specialists convincing focus on the origins of magical cognition and belief in the supernatural. In a two-part study, we reframe the problem by investigating relationships among ethnomedical specialists, who possess extensive theories of disease that can often appear "supernatural", vs. religious healing specialists. In study 1, we coded and analyzed cross-cultural descriptions of ethnomedical specialists in 47 cultures, finding 24% were also religious leaders and 74% used "supernatural" theories of disease. Using these data, we found correlates of the use of supernatural concepts, such as costly rituals, identify incentives and disincentives to patronize ethnomedical specialists, and developed a taxonomy of ethnomedical specialists that included prestigious teachers, feared diviners, and efficacious healers. In study 2, we interviewed 84 Maasai pastoralists and their traditional religious and non-religious healing specialists. We found that laypersons relied on medicinal services based on combinations of efficacy, religious identity, and interpersonal trust. Further, laypersons and specialists largely used abstract substance and essence terms to describe how local medicines work, rather than "supernatural" concepts. We conclude that religious healers in traditional societies often fulfill a practical and specialized service to local clients, and argue that "supernatural" theories of disease often reflect abstract cognition about rare phenomena whose causes are unobservable (e.g., infection, mental illness) instead of a separate "religious" style of thinking.

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1   Introduction

In his seminal work on comparative religion, Frazer (1890) considered shamans and other religious practitioners in small-scale societies to be performance artists without serious regard for scientific knowledge, notably stating that for them "magic is always an art, never a science" (p. 34). These individuals, who we refer to as *religious specialists*, invoke the supernatural while healing illnesses and performing divination rituals (Winkelman and White 1987; Eliade, Trask, and Doniger 2004). In the anthropological literature, "religion" is a family resemblance category referring to traditions that deal with activities such as ritual techniques for diagnosing the unknown, and "supernatural" concepts such as spirits, souls, and witchcraft (Needham 1975). In traditional societies, most religious specialists deal with practical problems such as health, illness, crop failures, or natural disasters (Peoples, Duda, and Marlowe 2016; Boyer 2020).

In practical task domains that can involve high stakes and uncertainty, such as medicine, it is unclear why specialists should use "religious" methods, particularly if using "scientific" ones would be a more effective strategy. This is especially puzzling for evolutionary theorists: What advantages, if any, could religious specialists gain by relying on religious methods for healing? And conversely, why should laypersons find religious methods convincing and/or pay costs to religious specialists as patrons? We address these questions by focusing specifically on specialists who deal with health, medicine, and illnesses.

1.1   A standard account: The subjective appeal of magical healing

An influential evolutionary explanation of religious specialization focuses on the origins of "magical thinking" as a cognitive byproduct. According to this view, human cognition is susceptible to supernatural beliefs and superstitious behaviors, which themselves are evolutionary byproducts of adaptive error management strategies: When an outcome is uncertain and false negatives are costly, adaptive strategies can include over-attributing agency to non-agents (Guthrie 1995) and spuriously inferring causes that appear "superstitious" to more knowledgeable observers (Foster and Kokko 2009). More generally, humans' adaptive capacities for reasoning about other minds, material artifacts, physical processes, and biological kinds might make "religious" ideas cognitively appealing (Kelemen 2004; Boyer and Bergstrom 2008).

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Most proponents of this view also argue that cognitive byproducts alone are insufficient for religion to gain traction, because the space of possible religious ideas vastly outweighs the space of those that culturally evolve in reality to become sacred, socially sanctioned religious ideas (Atran 2002). A complete evolutionary account of religion therefore requires an explanation of the social origins of religious institutions, in addition to its cognitive origins (Norenzayan 2015).

Explanations that complement the cognitive byproduct account focus on the social benefits of participating in religion, such as improved within-group cooperation, that offset the potential costs of participating in rituals or observing taboos (Wilson 2010; Chwe 2013). Religious specialists sometimes play a coordinative leadership role by publicly performing rituals, facilitating the spread of some religious beliefs over others by giving them "rehearsal time" at the social group level (Dennett 2006). These rituals are often costly, and one possible reason for religious specialists to gain traction is based on the subjective appeal of their displays to laypersons, which might attract the attention of admiration of potential followers (credibility enhancing displays; Henrich 2009; Singh 2018). The displays made by religious specialists, and the behaviors they inspire among religious followers, can provide societies with real benefits, such as improved between-group competitiveness (Norenzayan 2015), improvements to the local ecology (Purzycki 2016), social bonding, and/or ingroup signals of cooperative intent (Sosis and Alcorta 2003).

1.1.1 Convincing displays of supernatural ability?

Magical thinking about uncertain and high-stakes phenomena makes laypersons susceptible to exploitation, providing an opportunity for aspiring religious specialists. For serious yet rare events whose causes are opaque, such as many illnesses, laypersons could benefit by gambling on the advice of knowledgeable, trustworthy sources of information or aid (Morin 2015; Lightner and Hagen 2021). Religious specialists, on the other hand, could gain an advantage by using "plausible-seeming magical practices" that pander to intuitions about invisible and malevolent agents, with whom the specialist can negotiate to treat the illness. On this view, the religious specialist can gain prestige and patronage because the effectiveness of a magical practice is difficult to evaluate and/or prone to confirmation bias (Strimling, Enquist, and Eriksson 2009; Singh 2018).

Religious specialization might therefore represent a reliably-occurring, culturally evolved opportunity

for adapting to people's intuitions and convincing laypersons that the specialist can influence otherwise unpredictable and high-stakes outcomes (Singh 2018). Professionalizing this opportunity can (and often does) involve religious specialists who not only convince others of their supernatural abilities, such as healing, but also gain deference through fears of their abilities to impose harms and/or resources through patronage (Singh 2021).

Exploitation of cognitive byproducts fails to explain some important phenomena: Why do the areas of religious specialization so frequently relate to healing, e.g., compared to other unpredictable and high-stakes outcomes? And more importantly, if religious specialists are performers who use culturally evolved myths and customs that "hack our psychologies and placate our anxieties" (Singh 2018:17), then why should laypersons settle for the "religious" healer if a "scientific" one could be more reliable?

1.2 An alternative account: Religion, ethnomedicine, and a market for useful services

A mutually compatible explanation for religious specialization is that the "religious" healer *is* the "scientific" healer, and that patronage from laypersons is based on the actual efficacy of a specialist's treatments.[1] We refer to this idea as the *efficacious healing* hypothesis. People everywhere use folk scientific knowledge to make causal inferences and navigate uncertainty (Sperber, Premack, and Premack 1995; Szollosi and Newell 2020), and traditional knowledge systems are widely interpreted as providing useful, practical solutions for recurring challenges in a given socioecological environment (e.g., Glowacki 2020; Rappaport 1968; Steward 1972; Lansing and Kremer 1993).

In many societies, local specialists master elaborate systems of culturally evolved knowledge that require costly investments of time, resources, and opportunity costs (Lightner, Heckelsmiller, and Hagen 2021). Cross-culturally, medicine is one of the most common domains of folk scientific knowledge (Erickson 2007; Singer and Erickson 2011), and most adults in traditional and small-scale societies have at least some knowledge of medicinal plants and health-related practices, i.e., *ethnomedical knowledge* (Conklin 1980; Medin and Atran 2004; Lozada, Ladio, and Weigandt 2006). Nevertheless, even these societies typically have individuals who specialize in efficacious, culturally

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[1]We use "efficacy", like the standard definition in medicine, to refer to the effectiveness of a treatment method in obtaining its desired outcome.

evolved strategies for alleviating locally salient diseases (Berlin and Berlin 2015). We refer to these individuals, whose extensive medicinal knowledge can include herbal medicines, animal venoms, and human physiology, as *ethnomedical specialists*.

1.2.1 A market for efficacious ethnomedical specialists

Much research has focused on the cognitive, social, and ecological factors behind scientific knowledge (Carruthers, Stich, and Siegal 2002; Heintz 2007; Nersessian 2010; Thagard 2019), but the relationship between specialists and laypersons is less clear, particularly among ethnomedical specialists. What benefits, if any, do ethnomedical specialists provide to laypersons in traditional societies, and what benefits do the specialists gain in return?

People might favor knowledgeable ethnomedical specialists because they provide valuable services when stakes are high, especially for know-how that is inefficient to learn individually. If a service resolves a sufficiently uncommon and serious problem, such as an unlikely but deadly illness, then knowing how to diagnose and heal the illness can favor a market for specialized knowledge: for the average individual, the cost of mastering these skills might be greater than the cost of paying a specialist to do so, if and when the serious event arises. Ethnomedical specialists can therefore improve their own prospects by professionalizing an opportunity to provide valuable knowledge-based services, such as efficacious healing techniques, to their clients in exchange for benefits, such as payments or prestige. Clients do not necessarily learn the skills or knowledge underlying the service – patients who receive diagnosis and treatment do not thereby become doctors – but they might evaluate specialists based on individual-level feedback when they are recipients of specialists' services. We refer to this idea, which builds on the work of many others, as the *market for specialists* hypothesis (see, e.g., Hagen and Garfield 2019; Tooby and Cosmides 1996; Sugiyama and Sugiyama 2004).

Another view of the specialist-layperson relationship is that it is akin to mentorship. On this view, which we refer to as the *mentorship* hypothesis, experts possess valuable skills, and laypersons exchange deference for proximity so as to better acquire the skills for themselves (Boyd, Richerson, and Henrich 2011). Laypersons are not patrons *per se*, but are acolytes who can use ecologically rational cues to determine who to learn from: People might decide based on who others are copying

(Henrich and Boyd 1998), make judgments based on prestige (Henrich and Gil-White 2001), and/or perceive overlapping interests (Singh, Wrangham, and Glowacki 2017).

1.2.2 Is ethnomedicine "religious"?

The extent to which ethnomedical specialists resemble religious specialists is unclear. Historically, traditional scientific knowledge systems in Western and non-Western societies have included intuitive humoral and sympathetic concepts, e.g., among ancient Greeks, Quetzi Mayan, Ayurvedic, and Amharic Debtera medical knowledge systems (Young 1975; Atran and Medin 2008; Jaiswal and Williams 2016). To the modern Western observer, traditional ethnomedical concepts about infection, for example, might be easily interpreted as "religious" or "supernatural" based on their resemblances to spirits or magical contagion (Gottlieb 2004).

Conversely, religious healers such as shamans and priests employ esoteric and supernatural concepts in their practices, the medicinal and/or psychological benefits of which might help explain the evolution of religious ritual (Winkelman 1990; McClenon 1997). In at least some cases, they also display evidence of technical expertise in diagnosing and effectively curing illnesses with herbs (Andritzky 1989; Blackwell and Purzycki 2018).

We refer to the idea that ethnomedical specialists are also religious specialists (and vice versa) as the *religiosity* hypothesis. If "religious" specialists are also the "scientific" ethnomedical specialists, however, then how can we explain why they use supernatural theories of disease instead of naturalistic theories? Should laypersons weigh the relative importance of more "scientific" specialists vs. more "religious" ones?

1.2.3 A misleading distinction between science and religion

Social sciences have long assumed that practical and scientific concerns vs. religious ones are distinct aspects of both culture and psychology (e.g., James 1902; Frazer 1890; Weber 1920), and have largely developed their evolutionary theories of science separately from their evolutionary theories of religion.

This separation between scientific and religious practices has been carried forward to modern theories about distinct types of cognition (Shenhav, Rand, and Greene 2012; Funk and Alper 2015;

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Uzarevic and Coleman 2020), or at least of two separate positions on a continuum where religion is developmentally "natural" and science is not (McCauley 2013). This separation of religion, which seems intuitive, vs. science, which does not, might appear patently obvious and only motivate questions about *how* religion and science relate to each other (for a range of perspectives, see Barbour 1966; Draper 2009; Gould 2011; Coyne 2016).

Although scientific and religious *institutions* have a long and complex history of political and ideological cooperation and conflict among Western societies, the distinction between scientific and religious *knowledge* is relatively recent. Influential Western scientists, including Newton, Boyle, Hooke, and Kepler, were deeply religious and viewed much of their work as supplying evidence for a divine and transcendent creator (Gillispie 1996). The term "scientist" itself was not widespread until after the British Association's William Whewell coined it around 1834 as a suitable replacement for the term "natural philosopher". The term was meant to imply specialized commitments to creating knowledge (*scientia*, in Latin), analogous to the artist's commitment to creating art (Snyder 2012).

It is therefore not obvious that a distinction between "science" and "religion" is useful for analyzing beliefs and institutions in most non-Western societies. The modern Western institutional separation of science and religion might misleadingly lead theorists to carry this separation over into their evolutionary perspectives of cognition (Boyer 2018; Sperber 2018). In small-scale societies, anthropologists have documented uses of magic and religion for practical tasks involving high-stakes risk and uncertainty (Malinowski 1932; Evans-Pritchard 1940), often integrating *natural* and *supernatural* concepts into unified explanatory frameworks (Legare et al. 2012; Tucker et al. 2015).[2] In a classic example, Zande farmers understand the natural causes of unfortunate granary collapses (termites), but particular *occurrences* of these collapses demand supernatural explanation (witchcraft) (Evans-Pritchard and Gillies 1976).

At cognitive and behavioral levels, Westerners also integrate "scientific" and "religious" concepts by resorting to ritual in times of high-stakes uncertainty (Gmelch 1971), appearing to use magical thinking in experiments (Rozin, Millman, and Nemeroff 1986), and merging natural and supernatural explanations for life, death, and disease (Legare et al. 2012).

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[2]While *supernatural* is arguably an ethnocentric concept (see Sperber 2018), it is nevertheless central to defining religious belief systems in the existing literature. Indeed, this objection is an empirical claim, rather than an assumption, which we test in the present study.

1.2.4 Mental models about abstract and "supernatural" phenomena

The alternative account, involving a market for efficacious healers, therefore hypothesizes that "science" and "religion", while nominally distinct institutions among Western societies, are products of a cognitively integrated system whose evolved function is to acquire, exchange, and apply locally relevant social and ecological knowledge. Many anthropologists argue that religion should not be seen as a unitary phenomenon, nor that most societies have had "religions" in a useful sense of the term. Instead, small-scale societies, in which religion is not a hegemonic institution, have a variety of ideas, practices, and institutions that are described to varying degrees as "religious" in a loose and interpretive sense (Bloch 2008; Sperber 2018; Boyer 2020). That is, "science" is a culturally specific system for gaining practical knowledge (Heintz 2004), which might or might not include "religious" concepts.

It is therefore unclear that cross-cultural and evolutionary perspectives of scientific knowledge should exclude religious belief, and vice versa. Applied to ethnomedicine, the cognitive function of "supernatural" thinking about theories of disease might be to mentally model and make inferences about rare or abstract phenomena whose causes are unobservable (e.g., infection, mental illness, probability, counterfactuals) instead of a separate "religious" style of thinking.

1.3 Study aims and hypotheses

In a two-part study, we assessed the foregoing hypotheses about the roles of religiosity, efficacy, and knowledge specialization among ethnomedical specialists and their potential patrons. Study 1 was a cross-cultural study of ethnographic data from the electronic Human Relations Area Files (eHRAF), and study 2 was a field study with Tanzanian Maasai pastoralists.

In study 1, we assessed levels of evidence in cross-cultural data for attributes supporting the roles of *religiosity*, *efficacy*, *market specialization*, and *mentorship* among ethnomedical specialists. We exclusively searched the eHRAF for examples of ethnomedical specialists rather than religious specialists, meaning that any resulting ethnographic examples of religious specialists, efficacious healers, or prestigious mentors were not a consequence of our search query, but a consequence of their association with ethnomedical specialists in the ethnographic record.

In study 2, we investigated the criteria that patrons use to select among ethnomedical specialists, and their cultural models of medical treatments. Specifically, we interviewed 84 Tanzanian Maasai pastoralists about who they would favor among local medicinal specialists in the region if they were seriously ill and why. We also assessed cognitive models of disease by asking participants to detail their explanations for how a medicine for a common ailment works, and we introduce qualitative data from interviews with two local Maasai ethnomedical specialists and a traditional religious specialist. These interviews were conducted in a population undergoing a cultural and economic transition from pure cattle-based subsistence and trade, and toward a more Christian and cash-based market economy (Hodgson 2005).

2 Study 1: Cross-cultural data

We used cross-cultural data from the eHRAF to investigate the hypotheses that ethnomedical specialists are *religious*, offer *efficacious* treatments, compete for patrons in a *specialized market*, and are prestigious *mentors* who teach acolytes. We focused exclusively on ethnographic descriptions of ethnomedical specialists (i.e., without attempting to search for religious specialists), so we compared the extent to which each of these hypotheses, which were not part of our search terms, were supported by ethnographic evidence.

We also conducted extensive exploratory analyses at the text record level and the culture level. For example, we considered the correlates of supernatural theories of disease, religiosity, and acculturation, with acculturation interpreted as an "expansion" of pre-existing markets for ethnomedical specialists (e.g., via the introduction of infrastructure, hospitals and clinics, and/or foreign medicinal practices).

2.1 Methods

We searched for ethnographic data about ethnomedical specialists from the eHRAF, a digitized database of primary ethnographic documents from over 400 cultures around the world. We restricted our search to the Probability Sample Files (PSF), a stratified subset of 60 cultures in the eHRAF that includes one randomly selected culture from 60 geographically diverse areas (Naroll 1967). Documents in the eHRAF are coded at the paragraph level using an Outline of Cultural Materials (OCM) hierarchically organized coding scheme, containing several hundred numeric codes assigned

to unique and specific topics (Murdock et al. 2006).

Previously, in a study of ethnoscientific expertise (Lightner et al. 2021), we searched the PSF for 68 OCM codes that could plausibly result in descriptions of expertise in conceptual, folk scientific knowledge domains, such as ethnobotany, ethnometeorology, and theories of disease. We narrowed this search using six keywords that refer to highly knowledgeable experts in those domains, such as "expert*", "specialist*", and "practitioner*".[3] We did not include any OCM codes or search terms corresponding to religious topics. See the supplementary information (SI) for a more in depth summary of our search protocol, which produced 547 text records in total.

Whereas Lightner et al. (2021) broadly investigated the social characteristics of knowledge specialists that might explain knowledge specialization as an evolutionary strategy, and did not focus on their religious or supernatural qualities, here we restricted our investigation to *ethnomedical specialists*, resulting in 341 text records describing specialists with ethnomedical expertise. We included the 42 coded variables from Lightner et al. (2021) that characterized the knowledge domains and attributes (e.g., uses of plant knowledge) and social attributes (e.g., prestige) of ethnomedical specialists. We added 16 variables that characterized religious and supernatural dimensions of ethnomedical specialization, variables that would conceivably be important to patrons, such as the benefits and costs provided and imposed by specialists, and variables that indicated acculturation. This produced a total of 58 variables. See the SI for examples illustrating the text record coding procedure.

Our resulting dataset represented ethnomedical specialists in 47 cultures, whose geographic distribution and subsistence strategies are shown in figure 1. Our 58 variables allowed us to assess the extent to which ethnomedical specialists were *religious*, provided *efficacious services*, engaged in a *specialized market* for payment and patronage, and participated in *mentorship* as prestigious teachers. Similar to the variables in Lightner et al. (2021), many of these variables related to knowledge attributes and social attributes. See figure 2 for our coded variables and their corresponding attributes and hypotheses.

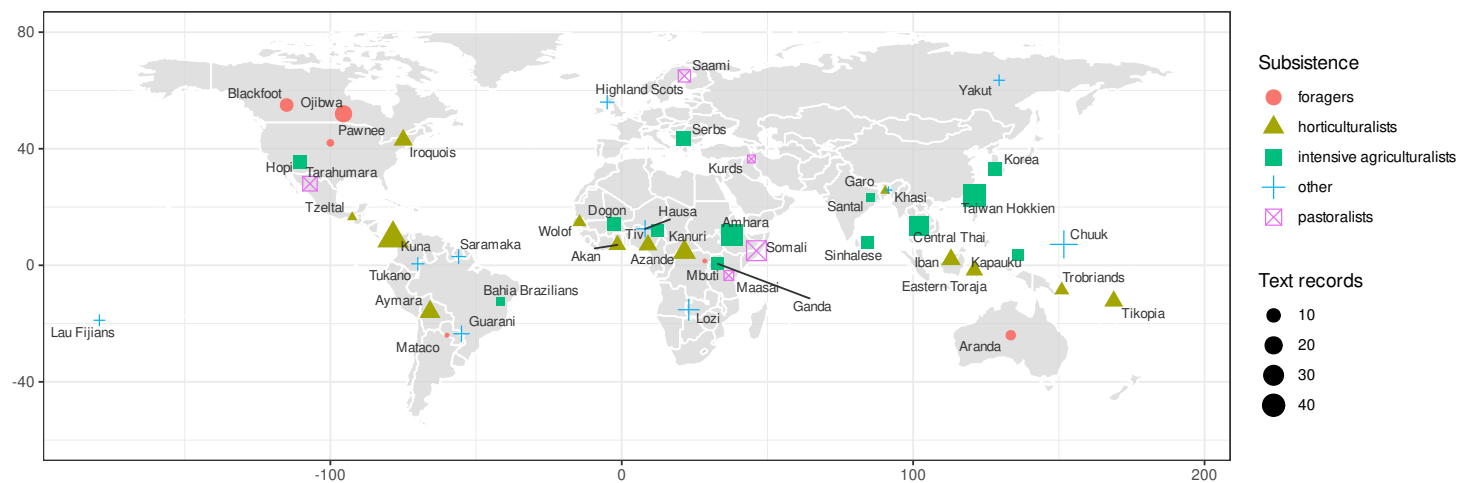[3]The "*" is a wildcard that would match any suffix.

Figure 1: Geographic region of each culture included in our dataset of ethnomedical specialists. Colors and shapes indicate subsistence strategy for each cultural group, and sizes indicate the number of text records for each culture in our dataset.

ADL and CH independently coded each text record for presence/absence (1/0) on each of our 58 variables, which generated a 85.5% match with a Cohen's kappa indicating moderate agreement (k = 0.49). Although most variables represented the presence or absence of evidence for a variable, in a few cases, it was feasible to code variables with evidence against one of our coded variables. We coded on variables for *prestige* and *specialist confers benefits*, for example, but we also coded on variables for *low status*, or "anti-prestige", and *specialist imposes costs*. See the SI for more details about interrater reliability. Afterward, ADL and CH discussed and reconciled all disagreements to produce the coded dataset used in our analyses.

Although most of our analyses were at the text record level, we were also interested in analyses at the culture level. We used the Standard Cross Cultural Sample (SCCS) to acquire variables at the culture level. The SCCS contained 44 of the 47 cultures in our eHRAF dataset, so text records from 3 cultures were excluded from analyses using the SCCS data.[4]

2.1.1 Statistical analyses

Our dataset comprised a 341 row by 58 column binary matrix, where each row represented one text record on ethnomedical specialists, and each column represented one coded variable (0=no evidence, 1=evidence). We analyzed this matrix in four ways. First, we computed the proportion of text records that provided evidence for each variable. Second, we grouped variables representing each hypothesis, and computed the mean proportion of evidence for each hypothesis (which we termed its *total score*). Third, we used hierarchical and penalized (elasticnet) regression models to determine the association of supernatural and religious concepts with other dimensions of ethnomedical specialization, the association of supernatural and religious concepts with culture-level factors, such as continental region, mode of subsistence, and cultural complexity (using variables obtained from separate SCCS data, and a principal components analysis (PCA) of these variables; Kirby et al. 2016), and the association of acculturation with dimensions of ethnomedical specialization. Finally, to examine structure in our entire data matrix, i.e., to determine which groups of variables tended to have evidence in the same text records and therefore might indicate important abstractions

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[4]The eHRAF data is our primary dataset of coded data from ethnographic text records about ethnomedical specialists, and should not be confused for the SCCS dataset that we used for this particular cross-cultural analysis. All references to "the data" or "the dataset" in Study 1 should therefore be assumed to be the eHRAF dataset, unless it is specified as the SCCS dataset.
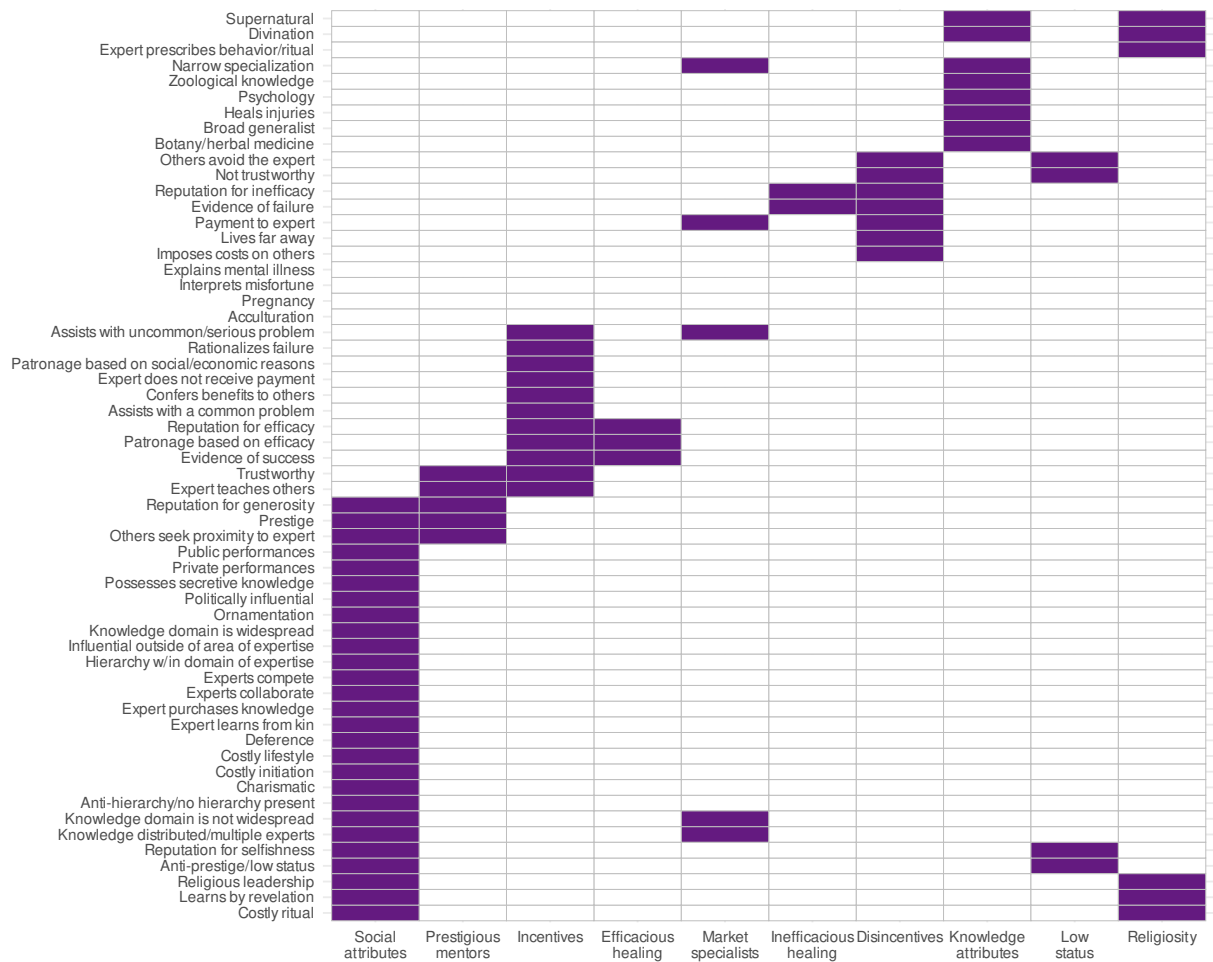
Figure 2: Coded variables about ethnomedical specialists are listed along the y-axis. The relevance of each variable to each hypothesis, and whether it is a social or knowledge attribute, is listed with its opposing model along the x-axis. Filled cells indicate which variables are included in each hypothesis and/or type of attribute.

about ethnomedical specialization, we used a network clustering technique known as a minimum spanning tree (MST), in which only similar variables (the vertices) are connected to each other. We then identified "clusters" of variables by visual inspection of the MST, seeking groups of adjacent variables that were conceptually related. For a full description of our statistical analyses, see the SI. We also provide all data and R code: https://github.com/alightner/ethnomedicine-magic.

2.2   Results

The text record level evidence for each of the 58 coded variables, which we broadly characterize as knowledge and social attributes, are shown in figure 3. We found high levels of evidence for supernatural theories of disease, uses of botanical knowledge, and narrow specialization. Text records frequently described multiple specialists who were distributed among separate roles with complementary specializations, often with collaborative relationships. In some cases, ethnomedical specialists were situated in a hierarchy with prestige, and engaged in public performances. Sometimes knowledge was clearly restricted to the specialists – in some of these cases the knowledge was intentionally kept secret – and sometimes the specialists were simply more knowledgeable and/or skilled compared to others in their society (figure 3A).

Most ethnomedical specialists (74%) used at least some "supernatural" concepts, such as witches, spirits, or deities. Some ethnomedical specialists had religious leadership roles (24%) and/or performed divination rituals during times of uncertainty (13%). When we grouped our variables according to hypotheses, their total scores showed relatively high levels of evidence for a market for specialists, efficacious healing, and religiosity. We found relatively less evidence for and against mentorship, and for inefficacious healing practices. See figure 3B.
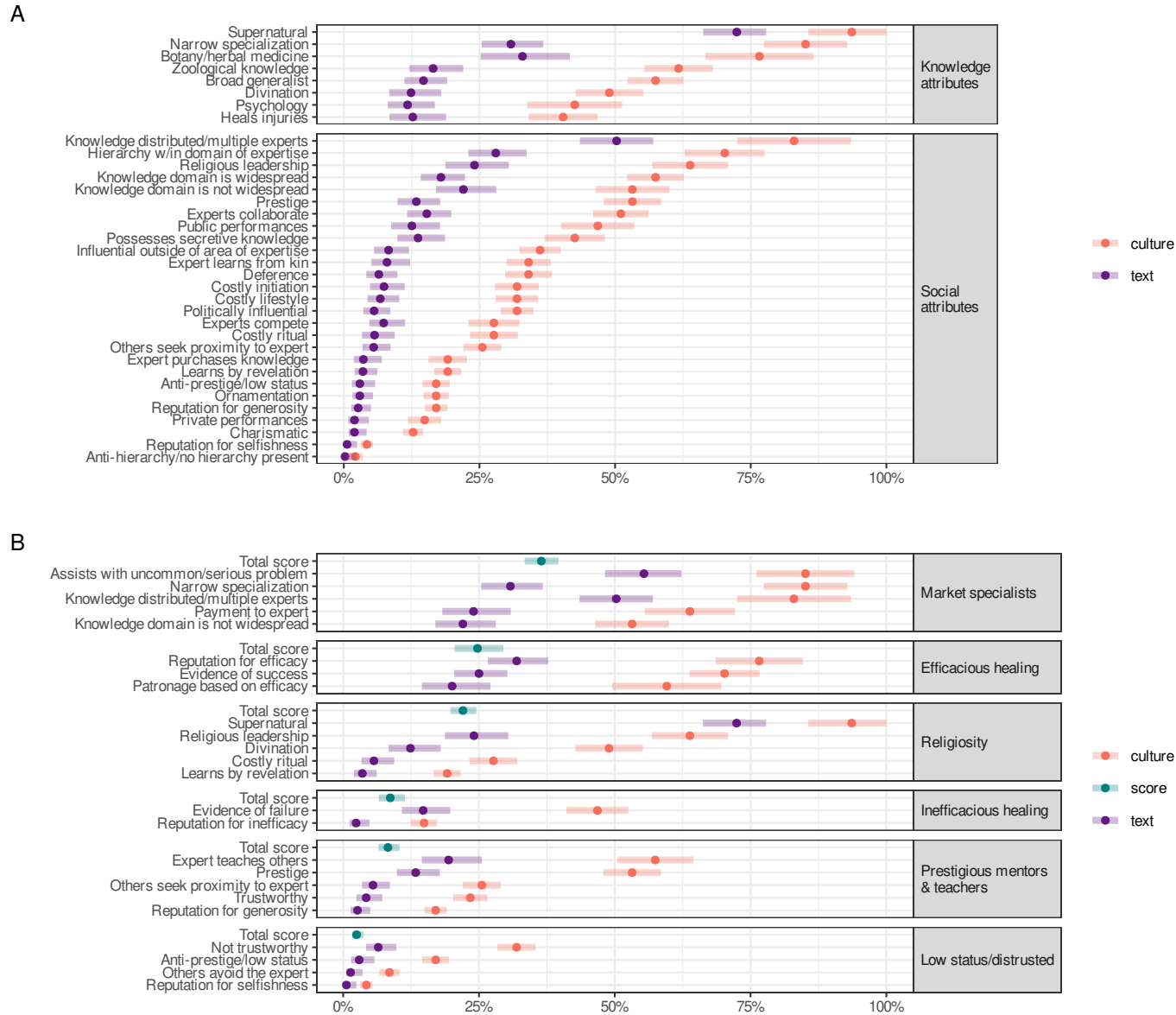
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Figure 3: Percentage of text records (purple) and cultures (orange) with evidence for each variable. A: Variables organized by knowledge attributes (upper facet) and social attributes (lower facet) among ethnomedical specialists in our eHRAF data sample. B: Variables organized by hypothesis. Total model scores are percentages of text records with evidence for any variable defining a given model. Error bars are +/- 2 SE. See the SI for more details on the estimate procedures.

2.2.1 Religion and the supernatural among ethnomedical specialists

The elasticnet regression model with religion scores for each text record as the outcome variable showed that variables most positively associated with evidence for religion were ethnospecialists assisting with uncommon and serious problems, imposing costs on others, specializing in theories of psychology, and possessing secretive knowledge. Religious ethnomedical specialists were also positively associated with multiple specialists whose knowledge was distributed across multiple roles. Predictors that were most negatively associated with evidence for religion were acculturation, purchased knowledge, and healing injuries (figure 4A). Neither regional variation nor subsistence strategy were associated with substantial variation in religion scores at the culture level (figures 5A and 5B).

The elasticnet regression model with presence/absence of supernatural theories in each text record as the outcome variable showed that the supernatural was positively associated with divination, costly rituals and initiation processes, and religious leadership. This model also showed that the supernatural was negatively associated with acculturation and evidence of success in their healing practices. See figure 4B. At the culture level, ethnomedical specialists' uses of the supernatural did not systematically vary by region or subsistence strategy, although intensive agriculturalists appeared to have less evidence for supernatural healing compared to horticulturalists (figures 5C and 5D).
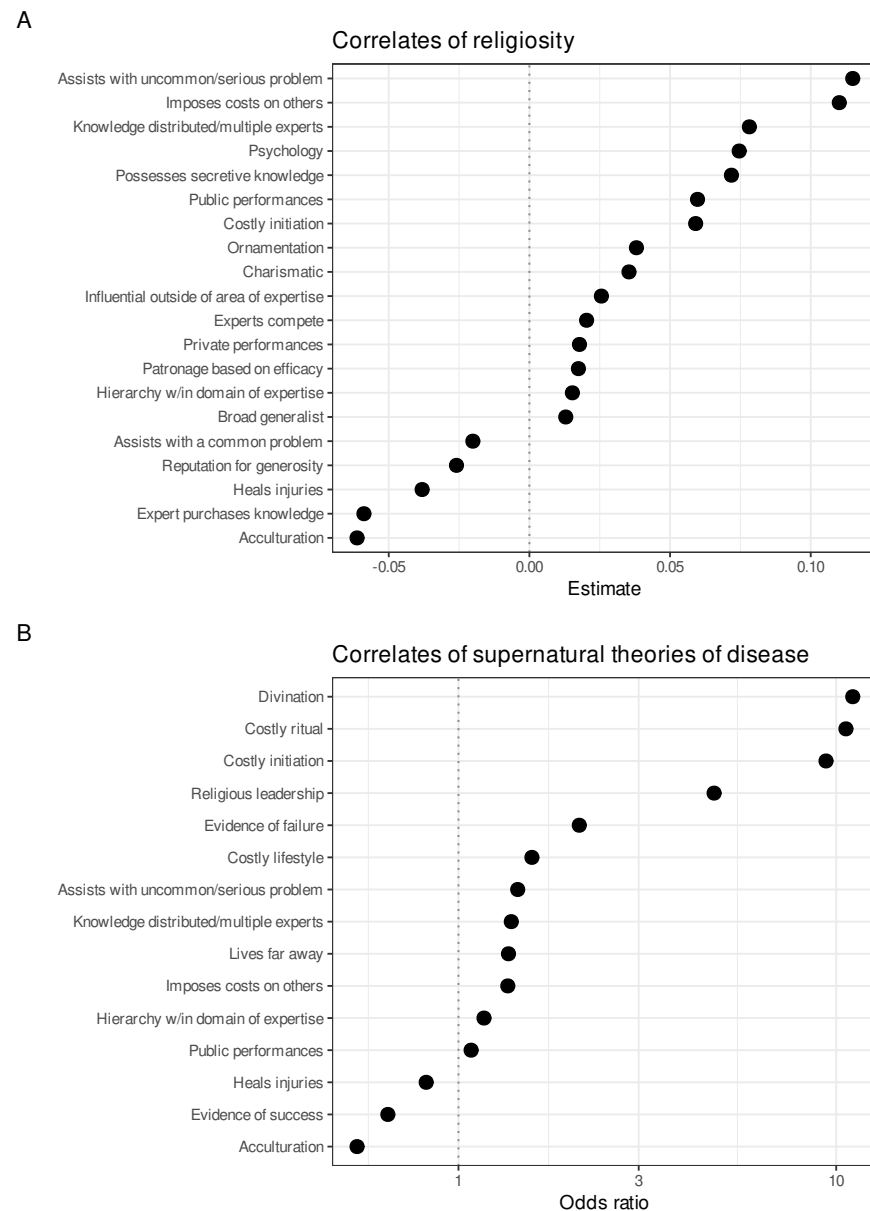
Figure 4: A: Regression coefficients from the elasticnet model of religiosity, where each presence/absence variable along the y-axis is a predictor and the total score for religiosity in each text record was the outcome. B: Regression coefficients from the elasticnet model, where each presence/absence variable along the y-axis is a predictor and presence of evidence for supernatural theories of disease used by ethnomedical specialists is the outcome. Estimates are reported as odds ratios. Note that the x-axis is log-scaled.
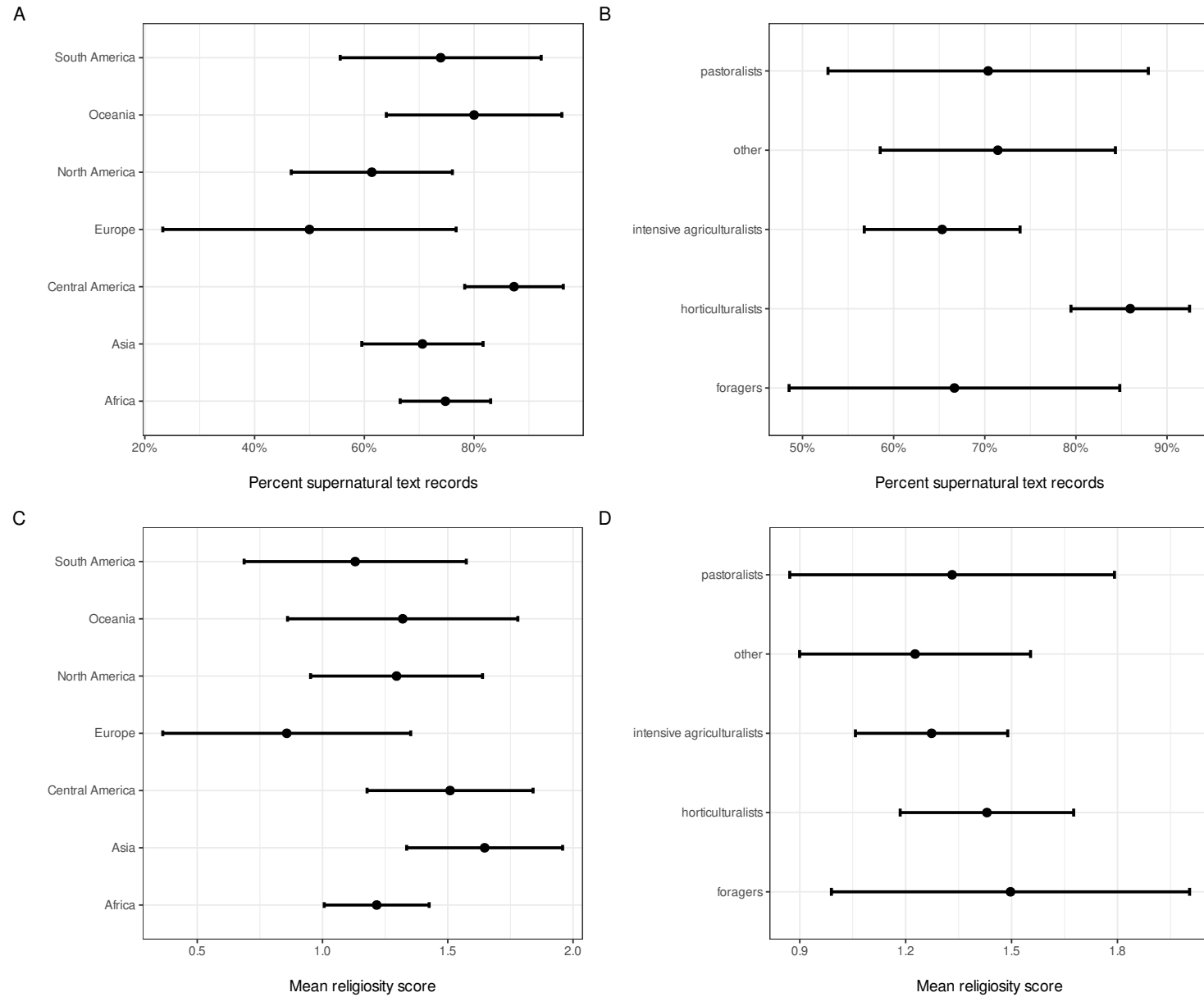
Figure 5: Estimated marginal means of religiosity scores by geographic region (A) and subsistence strategy (B) at the text record level, and for the proportion of supernatural theories of disease by geographic region (C) and subsistence strategy (D). Estimates are based on separate generalized linear mixed models with cultures as random intercepts. Panels A and B are based on poisson regression estimates, and panels C and D are based on logistic regression estimates. Error bars are +/- 2 SE.

2.2.2 Supernatural theories of disease are about the uncertain and the unobservable

Ethnomedical specialists often specialized in specific knowledge or skill domains, which included conceptual, ethnoscientific domains such as plant and animal knowledge. Supernatural theories of disease were more frequent in domains that are unobservable and uncertain, such as divination, misfortune, uncertainty, and psychology, and less frequent in domains involving some observable motor activity, such as physical injuries and childbirth (figure 6).

The first two components of a PCA of the 186 cultures in the SCCS data (see the SI) were interpretable as "culture complexity and scale" (PC1) and "pathogen stress and proximity to the equator" (PC2). See figure 7. We plotted the PC1 and PC2 values of the 44 cultures that were also in our eHRAF sample of ethnomedical specialists (3 cultures were not included in the SCCS). The eHRAF cultures that were higher on PC2 (i.e., higher pathogen stress, closer to the equator) appeared to account for many of the above-average proportions of text records with supernatural theories of disease (figure 8), a pattern supported by a regression model of the supernatural variable as a function of PC1 and PC2, in which PC2 is a significant predictor of supernatural but PC1 is not (see the SI for details and caveats).
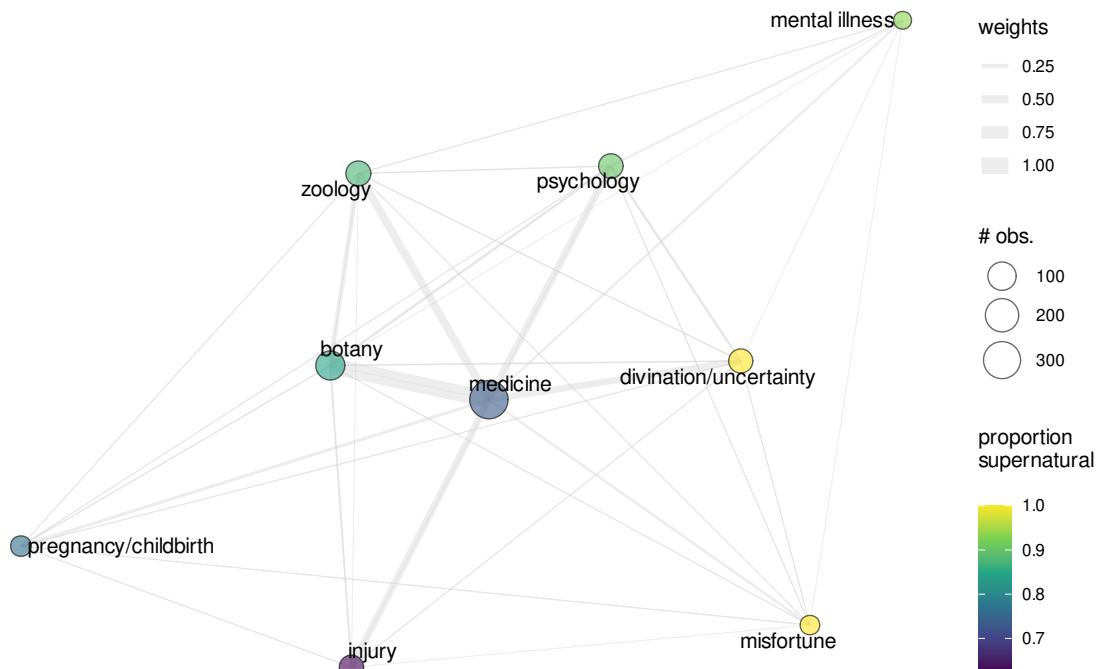
Figure 6: Graph representing commonly occurring domains of knowledge and skill that co-occurred with medicinal knowledge in text records in our dataset. Vertices indicate domains that occurred in at least ten text records, and vertex size corresponds to the number of text records including that domain. Vertex colors indicate the proportion of supernatural theories of disease that was associated with each knowledge domain. Each edge indicates that a pair of knowledge/skill domains co-occurred in at least one text record. Edge widths indicate the frequency with which each domain pair co-occurred, as determined by the number of text records describing them together, and normalized by the maximum frequency = 113.
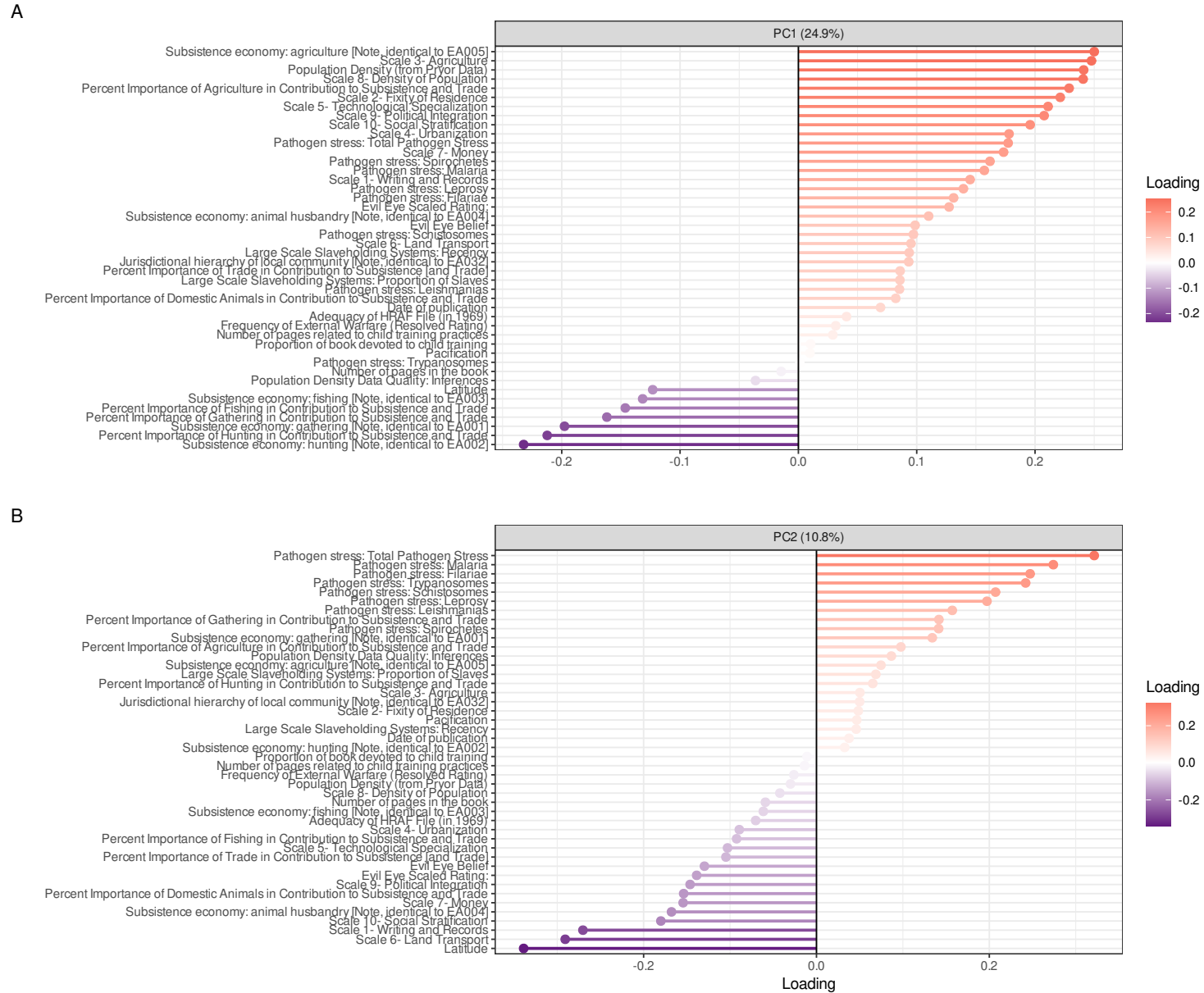
Figure 7: PCA loadings on the first two principal components in the SCCS dataset (sorted by loading values). A: PC1 corresponds to cultural complexity, population size, and societal scale. B: PC2 corresponds to pathogen stress, market and cash-based economies, and proximity to the equator (low absolute values of latitude).
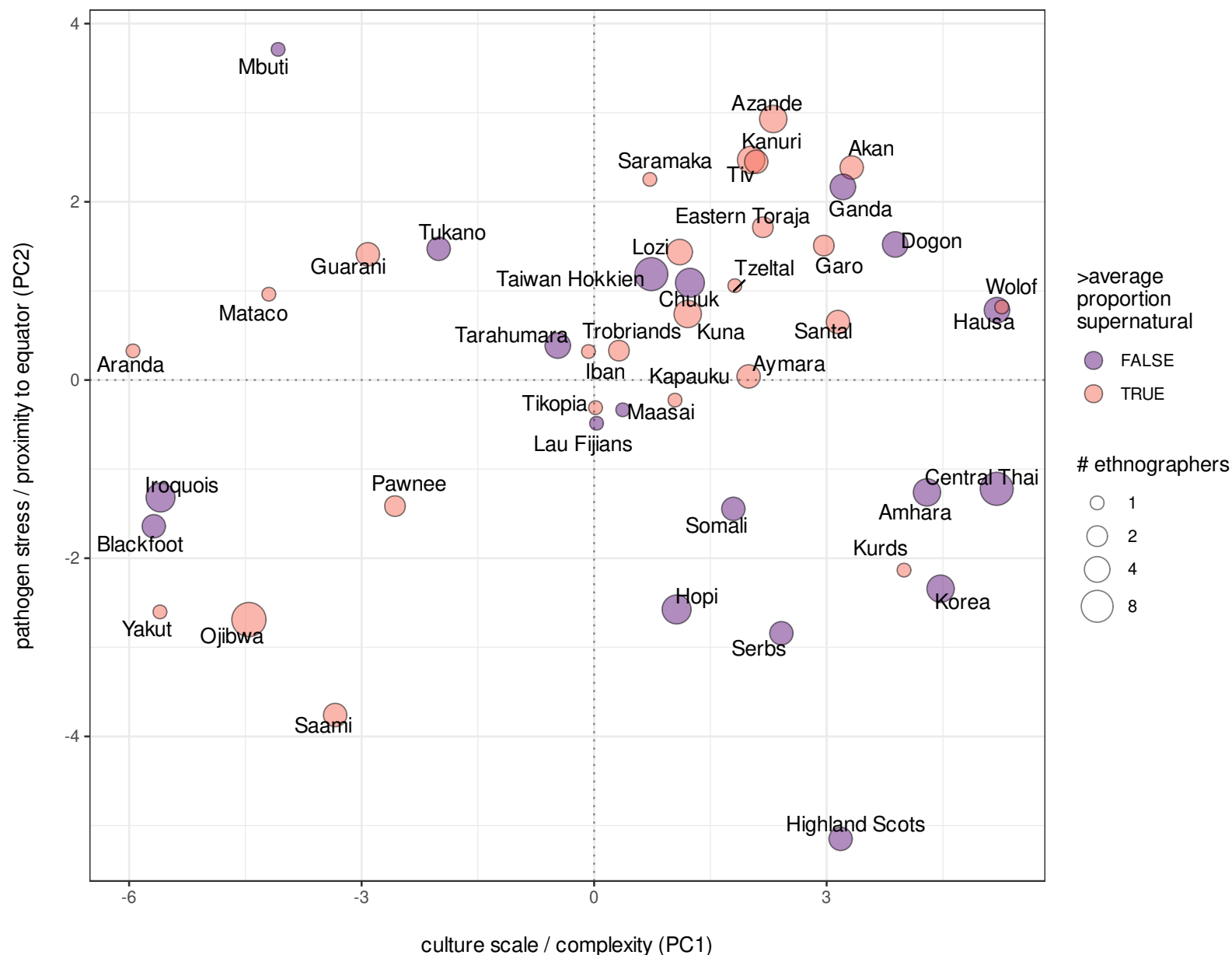
Figure 8: PC1 (cultural complexity) and PC2 (pathogen stress/proximity to the equator) values for each of the 44 eHRAF cultures that were in our study and the SCCS. (Note that cultures with large positive PC2 values are closer to the equator.) Point colors indicate whether each culture had an above average proportion of supernatural theories of disease, and point sizes indicate the number of ethnographers who contributed the text records about a culture.

2.2.3 Incentives and disincentives for patrons and acolytes

We found substantial evidence for the "market for specialists" variables and some evidence for the "prestigious mentors" variables (figure 3B). Here, we investigate the social relationships among ethnomedical specialists and laypersons as potential patrons and/or acolytes. Incentives for patrons and acolytes to favor ethnomedical specialists were more common than disincentives, and specialists often possessed rare and valuable knowledge (figure 9). Modeling pairs of incentives and their opposing variables – which were often disincentives – suggested that ethnomedical specialists usually conferred benefits to others, gained patronage based on their reputations for efficacy, assisted with uncommon and serious problems, were more often successful at healing than they were unsuccessful, and rarely offered their services for free. There was modest evidence for teaching. Evidence for trustworthy vs. untrustworthy specialists was about evenly split (figure 9).
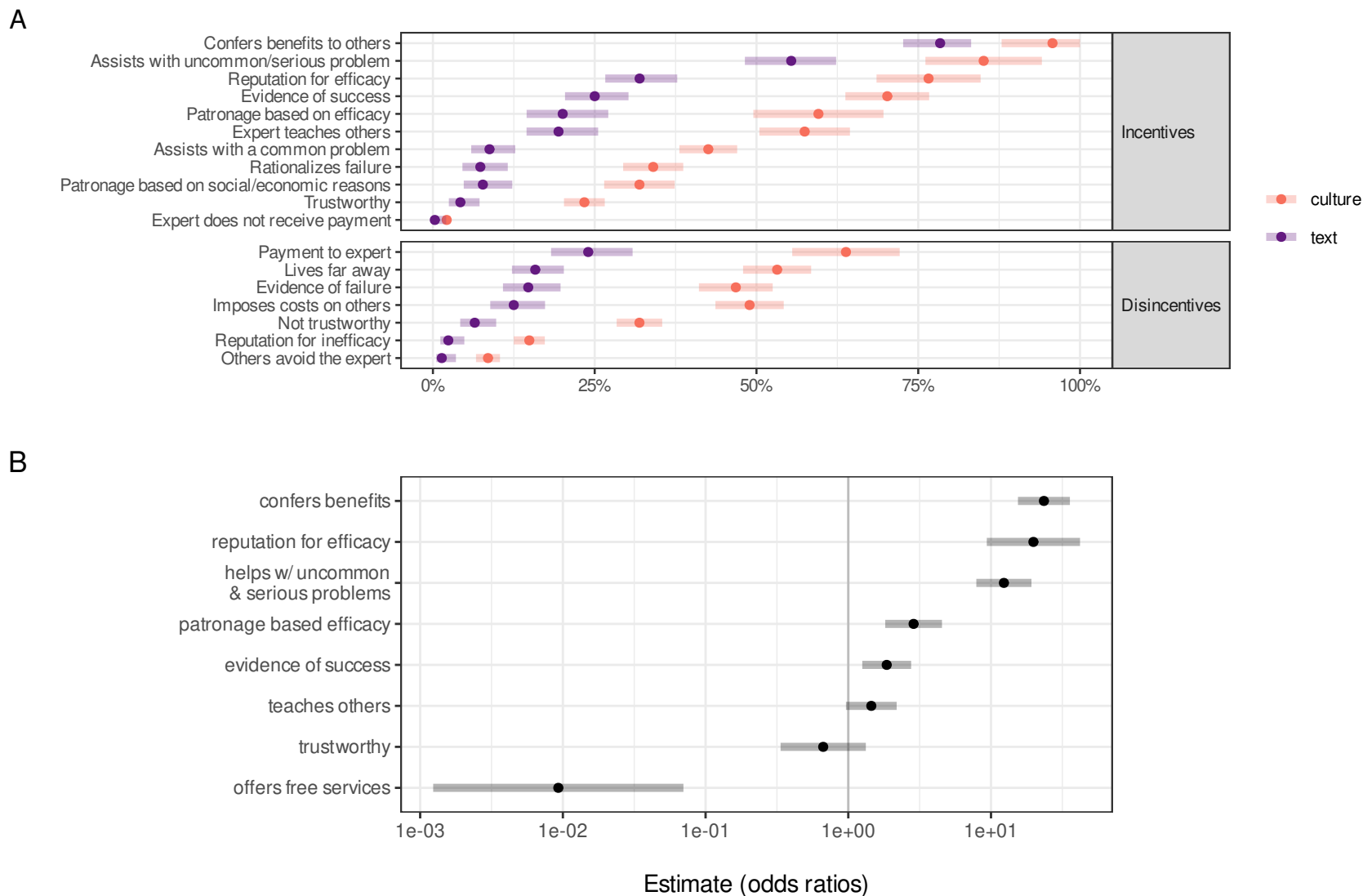
Figure 9: A: Text record and cultural group levels support for different incentives and disincentives that were associated with ethnomedical specialists in our eHRAF data sample. Points represent the percentage of evidence for that variable (the fixed-effect intercept from a generalized linear mixed effects model), and colors indicate whether that percentage is at the level of text record (percentage of text records with evidence), culture (percentage of cultures with evidence). B: Logistic regression coefficients among models of presence of evidence for vs. against each of the incentives for favoring ethnomedical specialists. Estimates are reported as odds ratios, and note that the x-axis is log-scaled. Error bars in both plots are +/- 2 SE.

2.2.4 Acculturation and market expansion

Acculturation was our proxy for expanding markets for ethnomedical specialists, and was positively associated with variables relevant to efficacious services, such as patronage based on efficacy, specialists with a reputation for efficacy, evidence of success and failure, and specialists conferring benefits to patrons. Acculturation was negatively associated with rare knowledge and variables relevant to religion, such as specialists prescribing ritual behaviors and supernatural theories of disease (figure 10).
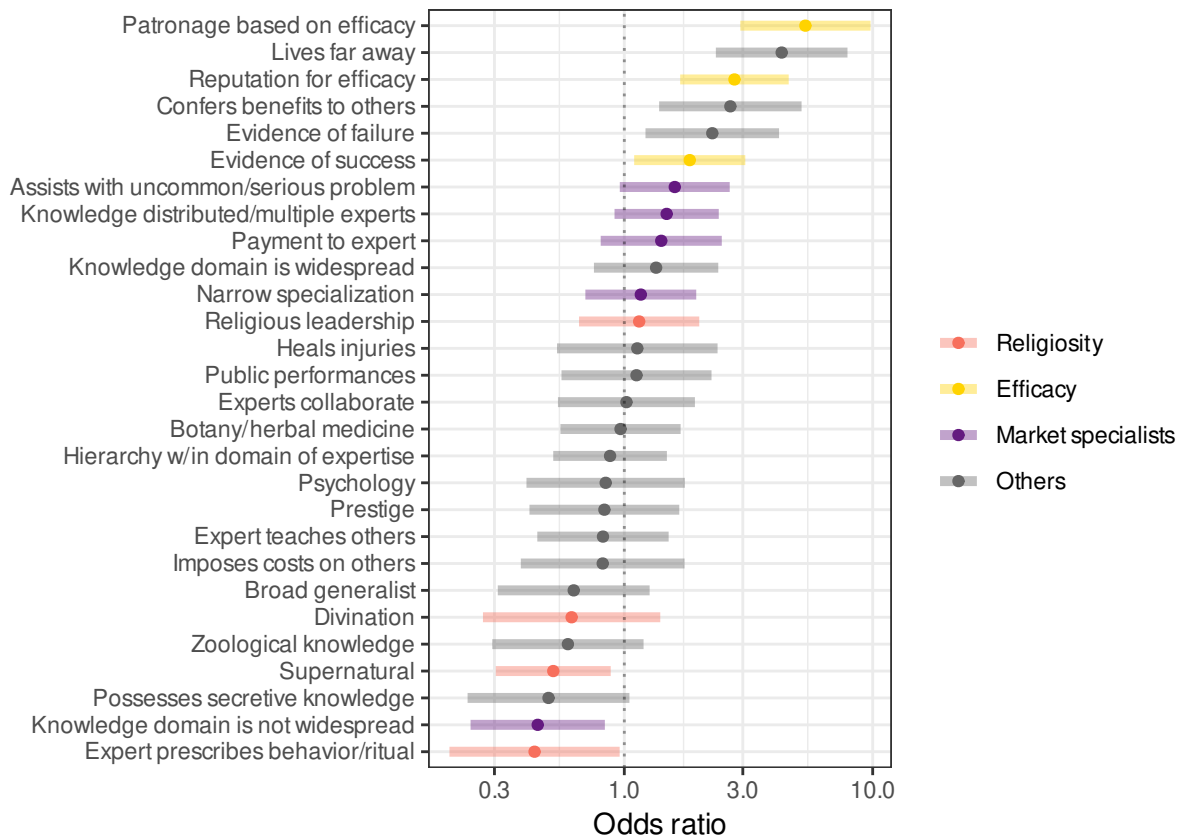

Figure 10: Fixed effects of acculturation on the proportion of text record evidence for each of the variables that had at least 10% support. Acculturation was the predictor in each GLMM and each variable listed along the y-axis was an outcome. Estimates on the log-scaled x-axis are reported as odds ratios. Error bars are +/- 2 SE, and colors indicate religious variables or specialized services.

2.2.5 Classifying ethnomedical specialists based on structure in the entire data matrix

Our MST revealed three branches of similar variables, which we interpreted as a taxonomy of three broad types of ethnomedical specialists: the "efficacious healer", the "feared diviner", and the "prestigious teacher" (figure 11). These interpretations are based on the variables within each of the three branches, which also contain informative sub-branches comprising similar variables. These three broad types of ethnomedical specialist are equally close to two central nodes at the root of our entire taxonomy: *supernatural* theories of disease and *religious leadership*.
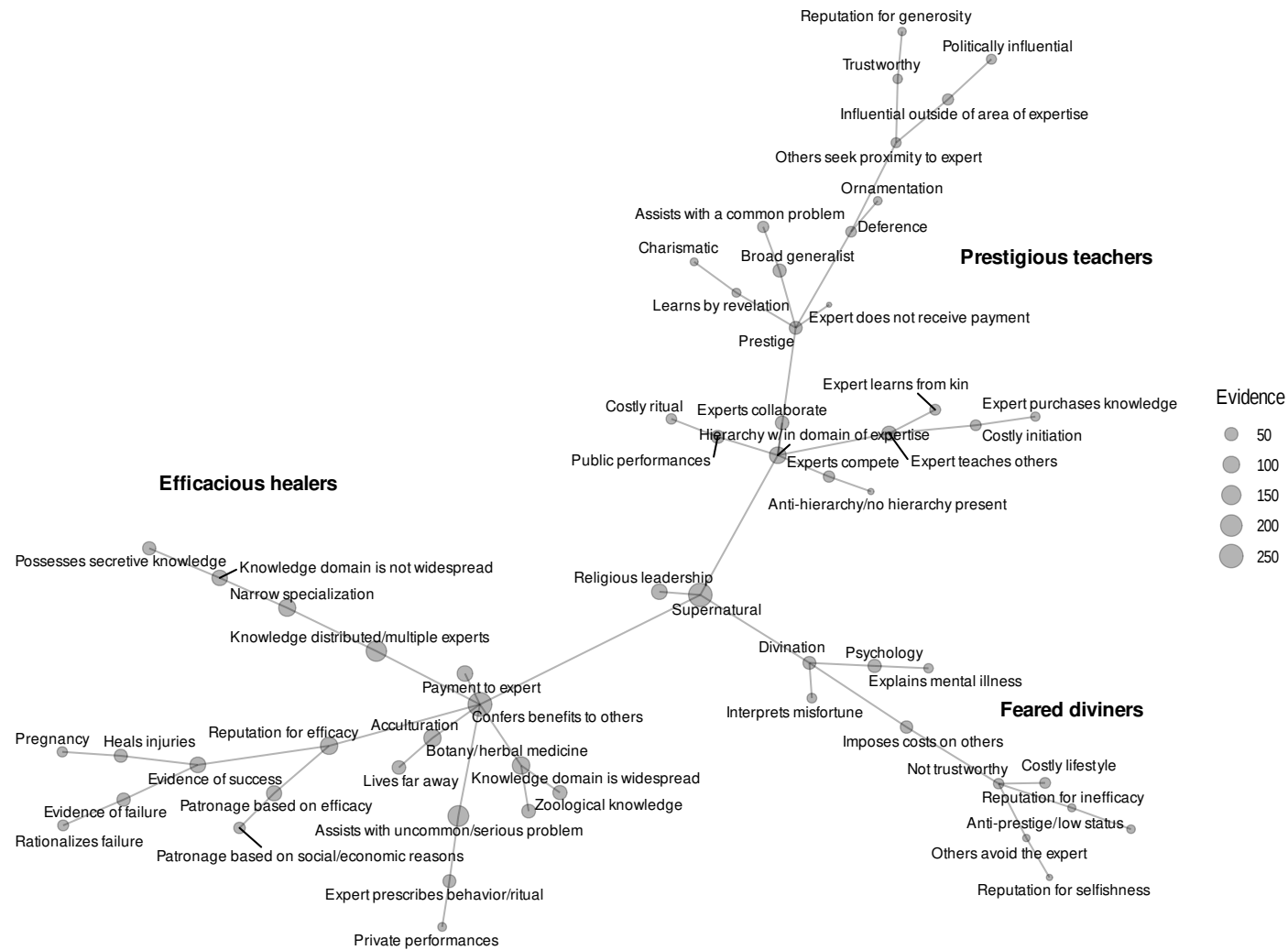
A taxonomy of ethnomedical specialists

Figure 11: Minimum spanning tree of the binary distance matrix of the variables in our dataset about ethnomedical specialists. Vertices represent variables, and vertex sizes correspond to levels of text record evidence for each variable. Edge lengths represent binary distances between variables. Annotations refer to our interpretations of each branch, which we interpret as a taxonomy of ethnomedical specialists.

2.3 Discussion of Study 1

Ethnomedical specialists were frequently sources of valuable knowledge, and provided efficacious treatments for specific, uncommon and serious illnesses. Although our search terms for eHRAF texts deliberately did not include religious topics, ethnomedical specialization nevertheless was frequently described as a "religious" occupation (figures 3 and 4). Specialists were often formal or semi-formal religious leaders such as priests and shamans, and in fewer cases, held politically influential roles. Most specialists across cultures, regardless of region or subsistence strategy, invoked "supernatural" concepts in their theories of disease, such as witches, spirits, or deities, and many also performed "religious" behaviors, such as costly rituals and divination during times of uncertainty (figures 4 and 5).

We found that supernatural theories of disease were more common among ethnomedical specialists who deal with conceptual knowledge about unobservable phenomena, such as interpreting mental illnesses or providing herbal remedies for infections, and were less common among those who deal with observable phenomena, such as childbirth and physical injuries (e.g., bone-setting and wound mending) (figure 6). Our PCA of the SCCS data found PC1 indexed culture complexity and scale, and PC2 indexed pathogen stress and proximity to the equator. Among cultures with higher pathogen stress (high PC2 values) – and therefore higher chances of serious illnesses due to infection – we saw a higher prevalence of supernatural theories of disease (figures 7 and 8). We caution that pathogen stress and proximity to the equator are highly confounded with many other relevant factors, such as money-based economies and agricultural intensification (the latter two also loaded on PC2).

As high levels of support for the "market for specialists" hypothesis suggested, many ethnomedical specialists served a practical function in their societies, regardless of their "religiosity" (figure 3). Incentives for favoring an ethnomedical specialist generally outweighed the disincentives, which were usually payments rendered for healing or teaching. Markets for specialists seemed to intensify with acculturation, which was positively associated with variables relating to efficacy, and negatively associated with supernatural theories of disease (figure 10). Acculturation, as coded by the OCM scheme and our coding protocol, often referred to a presence of Western medicine, such as nearby hospitals and clinics. Services were frequently for uncommon and serious illnesses, rather than

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common or everyday health issues (figure 9). We speculate that it is more efficient for laypersons to outsource sufficiently uncommon and serious problems to specialists rather than individually or socially learn solutions themselves (see also Hagen and Garfield 2019; Sugiyama and Sugiyama 2004).

We and others have argued that religion is at least partly an epiphenomenon of science, and the distinction between the two in Western cultures is primarily institutional (e.g., Sperber 2018; Boyer 2020). That is, supernatural concepts about "religious" entities vs. invisible forces invoked by "scientific" folk theories might share common cognitive characteristics (similar to the continuity hypothesis; Carruthers et al. 2002, p. 74). In our data, abstract essences such as bodily humors were not themselves coded as "supernatural", but they frequently co-occurred with the descriptions of spirits, ghosts, or other invisible agents that were. Indeed, Western folk scientific concepts about "germs" often resemble sympathetic magic or agentive thinking (Siegal 2002; Gottlieb 2004), and folk psychological concepts often invoke hidden invisible forces such as "souls".

We also found patterns that were not obviously explainable by efficacious or "scientific" healing practices: supernatural theories of disease were associated with religiosity, divination, evidence of failure, and costly rituals. This seems to suggest that at least some religious specialists in our data do not conform to our hypotheses about efficacious healing or a market for specialists.

The MST in figure 11 suggested a taxonomy, with three types of ethnomedical specialists emerging from structure in the data. We refer to the largest and most well-supported branch on this taxonomy as the "efficacious healers", the attributes of which are unified by *conferring benefits to others* and *receiving payment* at their root. Consistent with the market for specialists hypothesis, sub-branches included variables relevant to patronage, efficacious healing, and narrow specialists with rare and valuable knowledge (Tooby and Cosmides 1996).

The most diverse branch was "prestigious teachers", sub-branches of which generally conformed to the "mentorship hypothesis" (and many of the prestigious mentors emphasized in literature on social learning biases and cultural transmission, e.g., Richerson and Boyd 2005), along with prosocial and trustworthy leaders (Garfield, Hubbard, and Hagen 2019), and charismatic and prestigious shamans (Singh 2018). Perhaps unsurprising among ethnomedical specialists, we found less evidence for this

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branch compared to the "efficacious healers"; in a cross-cultural study of 55 traditional societies, Lightner et al. (2021) found that apprenticeships, mentorships, and other forms of social learning were associated with experts who were skillful in everyday tasks with easily observable motor skills, such as toolmaking and food preparation.

A third type, the "feared diviners", interpreted misfortune and psychological phenomena, and were characterized by traits that conflicted with our hypotheses about efficacious "scientific" healers, such as costly lifestyles, low status, and distrust among the laypersons who they might harm (Singh 2021).

Further supporting our conclusions about the centrality of supernatural concepts and "religious" specialization in medicine, these three types of ethnomedical specialists were unified by their mutual associations with religious leadership and supernatural theories of disease, central nodes in the MST.

3 Study 2: Maasai field data

In Study 2 among Tanzanian Maasai pastoralists, we focused on the criteria that patrons use to select among ethnomedical specialists when they become seriously ill, such as efficacy, religious identity, and/or interpersonal trust, and their cultural models of medical treatments.

The population we examined is currently undergoing substantial cultural and economic transitions that resemble the "acculturation" of Study 1, including relatively recent introductions of hospitals, clinics, and Christian churches. Additionally, we analyzed the extent to which Christianity predicted agreement in the statement that science and religion can conflict with each other, and how individuals' cultural models of how a medical treatment works compared to that of a local ethnomedical specialist. We primarily interviewed laypersons, but also include qualitative data from interviews with three ethnomedical specialists, one of whom also plays a traditional religious role in Maasai culture.

3.1 Methods

Fieldwork occurred in Monduli Juu highlands of northern Tanzania in a Kisongo Maasai village near two market integrated towns, each with shops, weekly markets, churches, and clinics. We conducted semi-structured interviews with key informants and a focus group, allowing us to identify local

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ethnomedical specialists during preliminary stages of fieldwork, and to establish the widespread perceptions about the hospitals and clinics, the church, and the traditional religious healer (the *laibon*) among the community. Key informants included Christian and non-Christian ("traditional") community leaders, locally salient ethnomedical specialists, and one of the several laibon healers in the region.

We conducted structured and semi-structured interviews with 84 Maasai adults in Monduli Juu (35% female) about their religious beliefs, trustworthiness of local religious figures, and on whom they rely to help them with a serious illness. To assess the criteria patrons use to select a specialist for medical assistance with a serious illness, we asked participants to list their first, second, and third ranked choices, the second and third choices assuming their condition did not improve. Responses to each of the foregoing questions were categorized as family, friends, a laibon (traditional healer), a church leader, a clinic/hospital, or themselves. We followed this with a series of questions about participants' religious identities; who they rely on most for spiritual advice; whether or not they trust the local church leadership, laibon healers, and doctors working at the clinic; and how frequently they attend church services.

To address the question of science and religion as separate or competing ideologies, we asked participants whether or not scientific ideas ever conflicted with their religious beliefs. If they confirmed that it did, we asked them to provide an example.

Finally, to examine the recurring abstract and/or "supernatural" features of ethnomedical explanations, we asked a subset of 58 participants to identify a common herbal medicinal treatment that they were knowledgeable about, and to explain how it worked against illness. We coded presence/absence of the following response features: *don't know*, *conditions* under which one should take the medicine (e.g., when a person feels chills), *substances* (e.g., blood, vomit), *essences* (e.g., illness is "driven out" by expelling a substance), *heat* (e.g., hot tea reducing chills in the body), *anatomy* and/or *physiology* (e.g., citing body parts and organs such as the stomach or kidneys, and/or describing how they interact with the medicine), *preparation* steps required for the medicine, whether or not it requires assistance from a *hospital or specialist*, citing *belief* that it works, and citing that *prayer* helps it work.

Participants were paid 10,000 TZS (about \$4.35) for their participation, and all protocols and survey materials were approved by Washington State University IRB and the Tanzanian Commission for Science and Technology (COSTECH) prior to data collection.

3.2 Results of semi-structured surveys and field observations

Maasai often have extensive practical knowledge about herbal remedies for common ailments (Heckelsmiller 2015; Roulette et al. 2018). Traditionally, the inexplicable and/or serious illnesses had been brought to the laibon, who plays a role as a healer and diviner in times of uncertainty (Spencer 2004).

More recently in Monduli, missionaries have had collaborative relationships with local community leaders, who have worked toward developing schools, churches, and privately funded clinics. Many clinics are run by physicians affiliated with missionary organizations, and are reputed as the most efficacious available option. Christianity has also seen a relatively recent uptick among locals in the area (Hodgson 2005), a departure from the traditional religious system in which the laibon healer is a trusted source of medical, social, and spiritual advice (Fratkin 2011).

3.2.1 Religious specialists: The traditional laibon healer and the Christian church

The laibon healers, who possess medicinal knowledge learned during apprenticeships with their fathers, still maintain regular clientele for serious illnesses. Laibon healers can only be males from a specific clan, and although they treat illnesses with tinctures and herbs, their knowledge and the contents of their medicines are inherited secrets. The laibon routinely charges a fee for his services. If he cannot help improve an illness then he might refer his client to another laibon or ethnomedical specialist in the region or, in more recent times, to a local clinic.

The laibon is also a diviner who practices clairvoyance. He uses an oracle horn to cast stones and interpret their configurations to guide him while preparing his medicines, gaining insight from *Engai*, the Maasai God. Although Engai has been described as an agent, similar in some ways to monotheistic gods (Hodgson 2005), the laibon likened *Engai* to "oxygen" during our interview, explaining that *Engai* is a "mind" in the sense that it represents the totality of knowledge.

The participants we interviewed were generally split in their perspectives on the laibon. For some,

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the laibon can help a person with serious illnesses, but also with bad luck, spiritual quandaries, or lost items. Many know one or more laibon healers through long-standing family friendships, and cite his importance to Maasai traditions. Others, however, distrust the laibon, considering him to be dishonest and insisting that the traditional reliance on him has been replaced by doctors and churches. A few participants were ambivalent, stating that the laibon is untrustworthy but nevertheless can help people when they need it.

Missionaries and church leaders were viewed in a similarly polarizing way. Some people noted that church leaders, local or otherwise, give people moral and spiritual guidance, pray for people to heal when they are ill, and give people hope in times of need. Others see the church as a business, using deceptive practices to collect money and resources. Some also noted that they have had little-to-no contact with, or interest in, the churches in the area.

The doctors employed at clinics were described in neutral to positive terms, with many interviewees stating that local clinicians are highly knowledgeable, trained, and experienced. Some described the trustworthiness and efficacy of clinicians in terms of their past experiences at clinics, where a doctor helped them improve after a serious illness or injury. Others were unsure what to believe about clinicians because they never went to the clinic, and preferred the laibon healers, friends, and the local ethnomedical specialists with whom they were familiar.

3.2.2 Ethnomedical specialists in Monduli Juu

The overwhelming consensus among key informants was that most clinics are the safe option for treating serious illnesses. In the rural areas of Monduli Juu, however, where fieldwork occurred, clinic access is often restricted by costs and travel distances, so friends, family, laibon healers, and ethnomedical specialists represent more personal and convenient options. We interviewed two reputable ethnomedical specialists, a younger man nicknamed Daktari Samuel (DS) and a respected older woman named Koko Nasari (KN). ("Daktari" is Swahili for "doctor" and "Koko" is Maa, roughly translating to "grandmother". "Samuel" and "Nasari" are pseudonyms.) DS and KN are both locally recognized experts in diagnosing specific illnesses in which they specialize, with DS focusing on herbal remedies for infections and "systemic" illnesses, such as cholesterol problems, and KN focusing on injuries and children's health. DS is a local botanical expert who sells herbal

medicines, which he grows and procures, for cash. KN treats muscular and gastric pains and general malaise (*ngongu*, or "evil eye") with massage, bloodletting, tooth extraction, and minor surgeries, sometimes in exchange for small payments. Similar to the laibon, each acquired their medicinal knowledge from their parents, but unlike the laibon they do not have formal and traditional titles. Instead, they gain their reputations through popular recognition of useful medicinal knowledge. For most participants, their salient social roles are as trusted friends or family members.

3.3 Results of the structured survey

In our sample, 61% of participants were Christian and 39% were traditional believers. Most participants (86%) did not see science and religion as conflicting under any circumstances. While a few did agree that scientific and religious ideas might sometimes conflict (14%), all of these participants were Christians. See the SI for examples given by these participants.

Participants overwhelmingly preferred to use the clinic in cases of serious illness. Many also preferred to use either friends, family, or religious specialists, such as the laibon and, in some cases, healing through prayer with church leaders. Religious options tended to be chosen mostly when other options failed. Although there was no strong religious disparity among those preferring the clinic as a first or second option, Christians tended to report that they would default to either the church or themselves if the clinic failed, or would not know to whom they should turn. (It is worth noting that help from church leaders often consisted of prayer and counsel rather than medicine.) Conversely, traditional believers often reported that they would turn to friends, family, or a laibon if the clinic failed. Some participants reported that they would seek a laibon first and a clinic second, and these were exclusively traditional (non-Christian) believers. More broadly, while Christians avoided the laibon and favored the church, and traditional believers avoided the church and favored the laibon, both Christians and traditional believers alike reported that they would often favor the clinic when serious diseases arise. See figure 12.
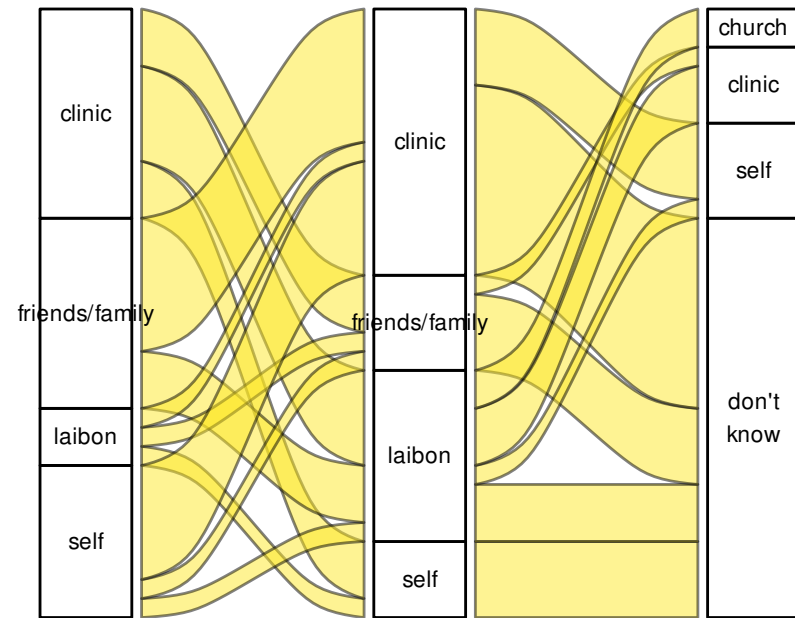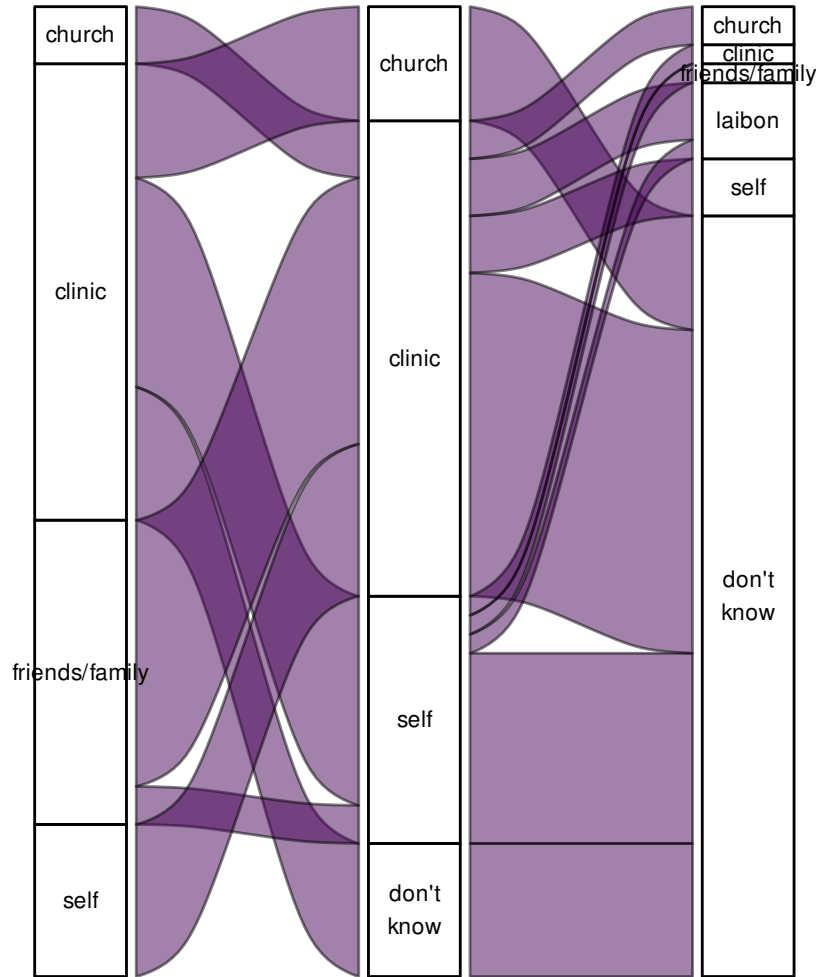
Figure 12: Alluvial plot of the proportions of participants who identified different types of specialists as their first (left) to third (right) choices to help them in the case of serious illness. Colors/facets are religious beliefs of the participants.

We conducted a PCA on the results of our surveys about interpersonal trust, spiritual advice during times of uncertainty, and patronage for serious illnesses, which revealed that participants did not sharply distinguish trust in medical advice from trust in other domains, and that these response patterns were at least partly split along lines of religious identity. Traditional believers were more likely to rely on the laibon for a serious illness, to personally trust the laibon, and to rely on him for spiritual advice. On the other hand, Christians were more associated with trusting church leadership, relying on elders for spiritual advice, attending church services, and soliciting help from the clinic for serious illnesses (figure 13).
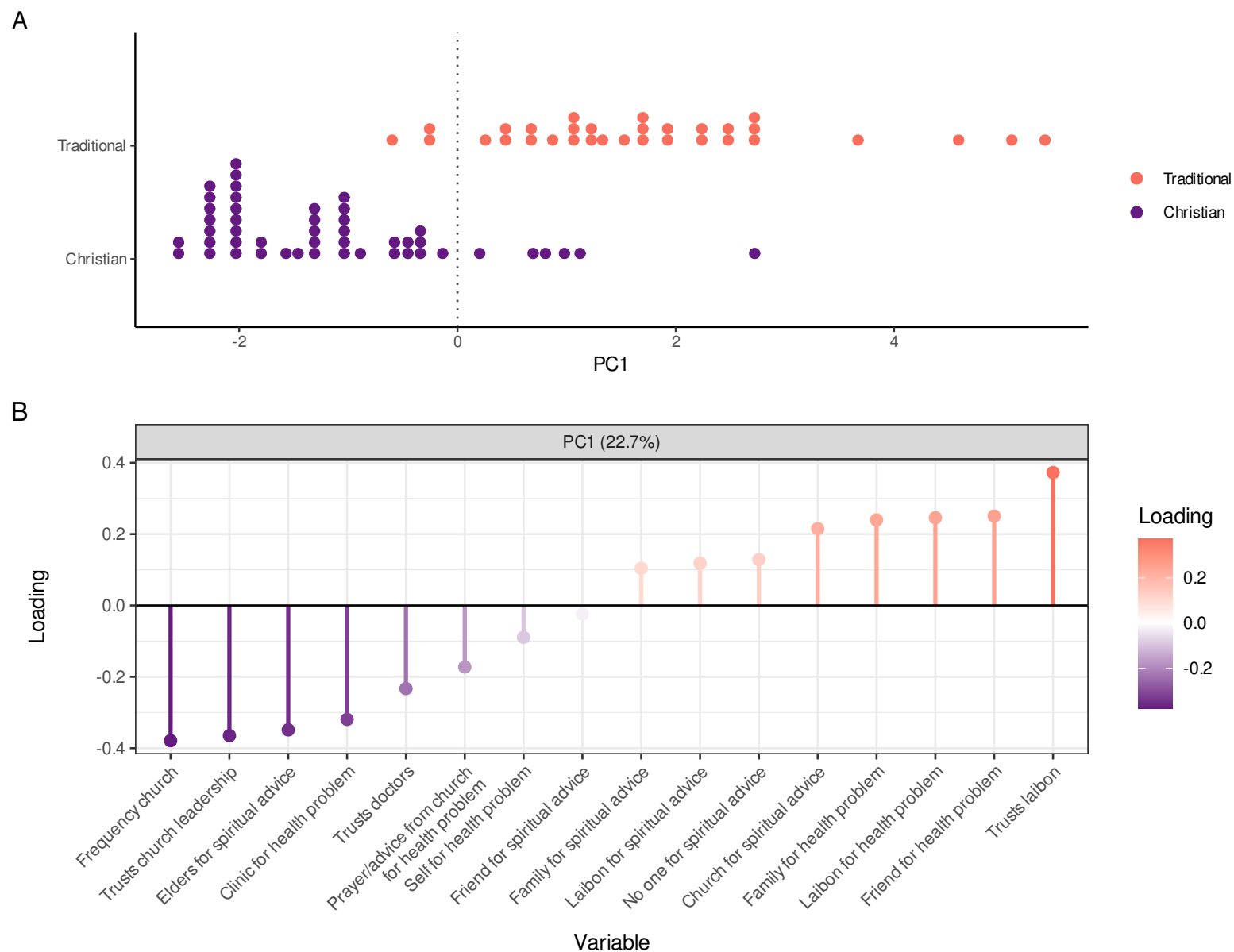
Figure 13: Variation among traditional and Christian participants on PC1: interpersonal trust, spiritual advice, and patronage for serious illnesses. A: PC1 values for each participant, colored by participant religious identity. B: PCA loadings plot with loadings on PC1 showing general trust in the laibon healer (higher PC1 values) and general trust in the church and elders (lower PC1 values).

3.3.1 Explanations of how herbal medicines work

We asked a subset of 58 participants to identify and explain how a common herbal medicinal treatment works. Their explanations largely fell into three groups: participants either (1) stated that they did not know how it worked, but only *that* it worked (which we term "don't know"); (2) stated that they only knew the conditions under which one should take it while listing the steps to prepare the medicine, and/or citing "belief" that it works or that they pray it will work (which we term "how-to"); and (3) explained the mechanisms in terms of substances, essences, heat, and/or anatomy and physiology (which we term "mechanistic"). See figure 14 and the SI for PCA results.
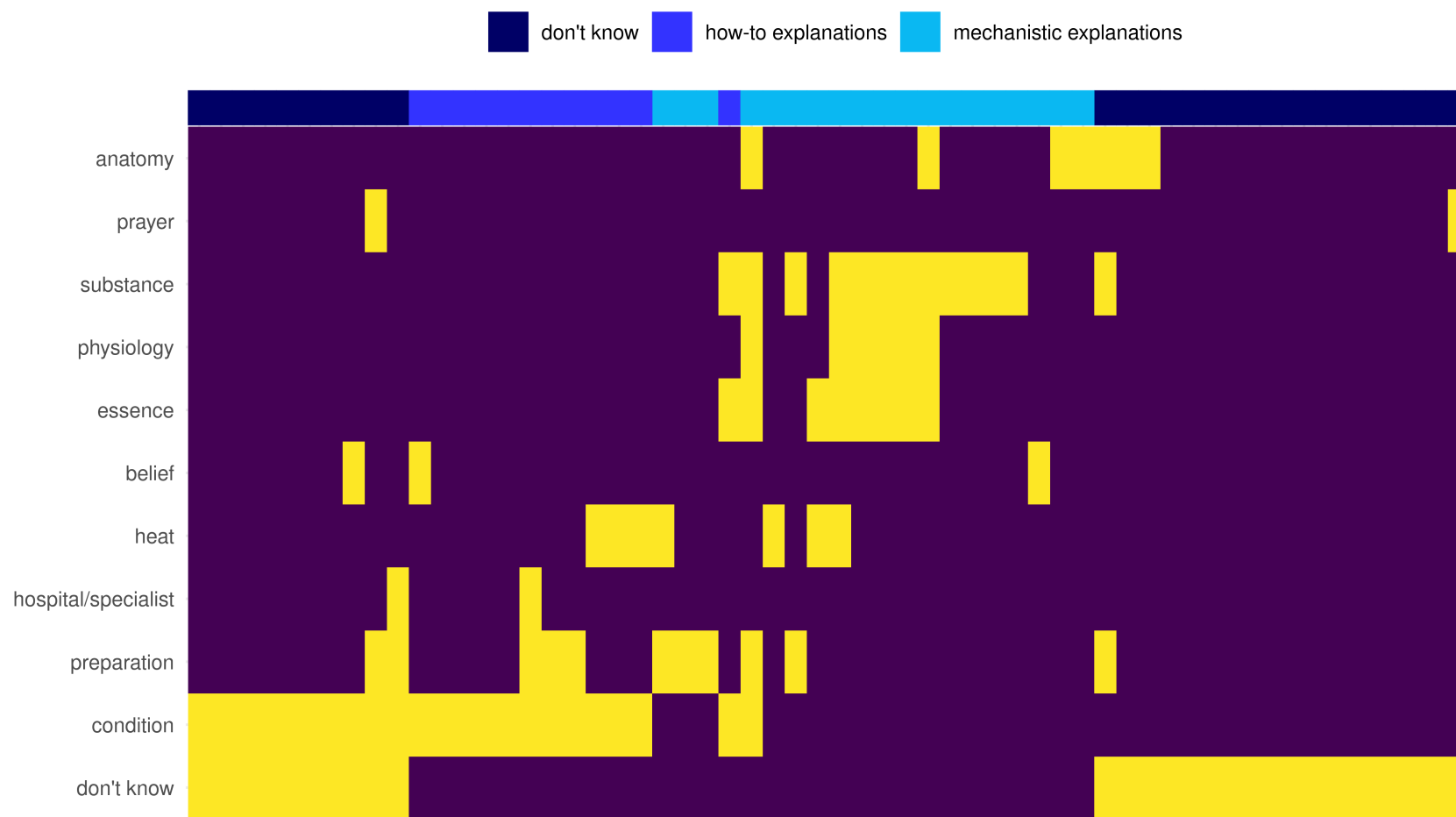
Figure 14: Explanations of how common herbal medicines work. Each column is one participant. Each row is a feature that was present in (yellow) or absent from (purple) each participant explanation. To group participants by their types of explanations, rows and columns were ordered using the PCA angle seriation method. Annotations along the top identify three broad types of explanations.

3.4 Discussion of Study 2

Our survey of Tanzanian Maasai pastoralists, in a setting where cultural and economic changes include recent influxes of Christianity and clinics ("acculturation"), had two primary goals.

Our first goal was to investigate the criteria that patrons use to select an ethnomedical specialist when they become seriously ill (e.g., efficacy, interpersonal trust, religious identity). Most participants preferred to use the clinic when seriously ill, which was described as the most efficacious option among most key informants and participants. Participants who trusted the doctors from clinics largely cited their past experiences with treatment, despite their generally impersonal relationships with the doctors who work there. Others preferred to rely on friends, family, and religious leaders who they personally trusted, and who, in contrast to the clinics and hospitals, were conveniently nearby. Preferences for the clinic appeared to be mostly independent of religious affiliation, but religious identity became relevant if a non-religious option, such as the clinic, were to fail (figure 12.

These results elaborate on the "patronage" variables of Study 1 (based on efficacy vs. socioeconomic considerations): although expected efficacy from ethnomedical specialists was important, this preference was at least partly constrained by social considerations, such as religious identity and trustworthiness (figure 13), and by economic considerations, such as distance traveled, cost, and accessibility.

Christians often commented that they distrusted the laibon, avoided him, and believed that he deceives people for financial gain. In this way, the Christian perspective of the laibon resembled the "feared diviner" of Study 1. On the other hand, traditional believers, who trusted the laibon as an "efficacious healer", similarly viewed the local church leadership as untrustworthy. The causal relationship between religious identity and participants' response patterns remains unclear, and future research can further explore whether religious beliefs motivate a preference for some specialists over others, or actual benefits from some specialists are motivating religious commitments to their belief system.

A key idea for the "market for specialists" hypothesis is that specialists possess useful knowledge about uncommon and serious illnesses, the value of which is based on the specialist being irreplaceable (Tooby and Cosmides 1996). An example of this would be medical treatments that are "proprietary",

or secretive knowledge (figure 11). Our qualitative data showed mixed support for this. Consistent with proprietary knowledge, the laibon, a traditionally preferred specialist for treating inexplicable and serious illnesses, declined to explain how he understood his medicines to work, and explained that his knowledge was an inherited family secret. On the other hand, DS and KN openly explained at least some of their treatment methods to clients and interviewers, and nevertheless made livelihoods using their skills.

Our second goal was to investigate the extent to which "religious" ideas were distinct from "scientific" ones. We found that science vs. religion was a largely unintuitive distinction for most Maasai participants, and that the few who recognized the distinction (14%) were exclusively Christians who were able to give specific and familiar examples, such as "sometimes scientists say there is no god, which I disagree with" (see the SI for details).

When we asked laypersons and specialists to explain how medicines worked to heal the body, those who attempted to explain the underlying processes almost uniformly responded in terms of abstract forces that were not "religious" – with the exception of a few people saying that they would pray for an improved condition (figure 14). Instead, common illnesses were explainable in abstract terms that do not clearly resemble the "supernatural", and although religious behaviors (e.g., prayer) were sometimes advocated as potentially helpful for the medicines' effectiveness, they were rarely invoked as a component of its explanation (Tucker et al. 2015). More serious illnesses were associated with patronage to a clinic or specialist rather than self-care.

The main exception to this pattern was the "religious" laibon healer, who used clairvoyance from *Engai* and divination with an oracle horn, to deal with inexplicable illnesses. Nevertheless, the laibon's description of Engai as an ethereal force whose "mental" properties are akin to a totality of knowledge might suggest that the "supernatural" concept of Engai is simply an abstract metaphor (see also Evans-Pritchard 1953). Future research could therefore benefit from questioning the extent to which "religious" concepts that appear patently supernatural (e.g., Engai, or "god", as an agent) are, in fact, at least partly overlapping with abstract but naturalistic metaphors (e.g., Engai, or an "ethereal force", representing the totality of knowledge).

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4   General Discussion

Influential models of cultural evolution emphasize the transmission of important skills, such as tool manufacture or food preparation, that are frequently used by most members of the population (Boyd et al. 2011; Henrich 2016). This view corresponds to one of the three main branches of our MST, the "prestigious teachers" (figure 11). Yet the ethnographic record is replete with descriptions of knowledge specialists, such as shamans and healers, who have proprietary knowledge that they use to solve uncommon and serious problems, such as illnesses. An individual's expected benefit of mastering solutions to rare problems might be low: By definition, the problem might rarely or never arise, and building and maintaining expertise can be costly. In a large population, rare and serious problems will nevertheless occur to someone, so there will be demand for knowledge specialists who can solve those problems (Sugiyama and Sugiyama 2004).

As studies 1 and 2 suggest, ethnomedical specialists often provide practical solutions to unobservable and uncertain problems for payments (see also Lightner et al. (2021)), and clients largely base their patronage on efficacious outcomes (figures 9A and 12). Indeed, we sometimes even observed clients deferring to specialists they did not necessarily trust (figure 9B). Ethnomedical specialists can benefit by gaining a clientele that is willing to exchange payment for services such as diagnoses and treatments, whereas clients benefit by outsourcing these tasks instead of acquiring expertise of their own (Hagen and Garfield 2019). This view corresponds to a second major branch of our MST, the "efficacious healers" (figure 11).

This is not to suggest that other considerations are unimportant, such as prestige, social norms, and convenience (which we referred to as socioeconomic factors; see figure 3). On the contrary, Maasai participants often preferred nearby family and friends over clinics for treating illnesses, and preferences for religious figures were aligned with religious beliefs and trustworthiness (figure 13). We also saw support for this pluralistic approach to client preferences among specialists in the ethnographic data, where clients would primarily select a specialist based on their efficacy, among other socioeconomic considerations (figure 9).

These points echo an important caveat about markets, namely, that transaction costs (e.g., energetic requirements, information scarcity) constrain efficient market dynamics (North 1990; Ensminger

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1992). Such considerations might help understand why some Maasai participants often preferred family and religious figures over clinicians that they never met, and why we saw a similar trend in the ethnographic data.

4.1 Religious and non-religious ethnomedical specialists

Specialized knowledge typically comprises a combination of what Western scholars would characterize as "scientific" and "supernatural" or "religious" concepts. One view of the religious and supernatural services provided by specialists is that they are credible displays that serve to convince observers that the specialists can control unobservable forces (Henrich 2009; Singh 2018). This view corresponds to a third branch of our MST, the "feared diviners" (figure 11).

Nevertheless, ethnomedical specialists ("efficacious healers") were often "religious", and the "supernatural" and "religious leader" nodes were equally close to each of the three major branches of the MST (figure 11). One possible interpretation of these results is that religiosity somehow benefit the client. Shamans and similar healers routinely dispense herbal medicines with accompanying rituals, and these rituals might serve supplementary social functions (Winkelman 2010) or even enhance the efficacy of the substances consumed by a client. Shamans often assist with ailments that are accompanied by psychological stress and its associated symptoms, which are amenable to placebo-effect treatment (McClenon 1997; Sosis 2007). Indeed, this is consistent with findings in study 1, where specialists sometimes used costly and religious rituals, and study 2, where prayer and religious figures were important parts of dealing with serious illness.

Another possibility is that a specialist's "supernatural" concepts represent folk intuitions about unobservable or abstract scientific kinds, such as germs, life, chance, or minds (Siegal 2002; Gottlieb 2004; Howell 2012). For example, although modern medicine has delivered incredibly detailed and rigorous bodies of knowledge about viruses and bacteria, Western educated laypersons nevertheless tend to possess vague concepts of disease-causing agents that might appear magical or superstitious (Rozin et al. 1986; Keil et al. 1999; Legare et al. 2012). This is consistent with the idea that categorization of the "supernatural" vs. the "natural" requires interpretation by ethnographers and readers, which are built from a culturally contingent (often Western) framework (Sperber 1985) that is based on an *a priori* separation of science and religion.

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According to this view, "religious" and "supernatural" are not only polythetic terms, but arguably ethnocentric descriptions of a variety of unrelated phenomena (Engler and Miller 2004; Bloch 2008; Schilbrack 2010; Sperber 2018). How, for example, should bodily humors, spiritual essences, or magical contagion be disentangled from Western folk theories about life, consciousness, or transmissible illnesses? In the text records in study 1, "natural" concepts, e.g., about plants, animals, and physical injuries, frequently co-occurred with supernatural ones (supernatural+natural: 49%, supernatural only 25%, natural only 21%). In study 2, a separation of science and religion was only observed among Christians, i.e., those who were familiar with this institutional conflict that is arguably idiosyncratic among Western societies.

4.2 How does acculturation impact a market for specialists?

When markets for specialists expand to accommodate new ideas that did not traditionally exist (acculturation), both studies suggested a higher frequency of patronage based on efficacy, and a lower frequency of reliance on supernatural knowledge and/or religious specialists (figures 10 and 12).

For clients, we interpret these outcomes as a result of an expanded market for specialists: more options beget a more competitive market. All else equal, clients can "shop around" for more efficacious specialists with proven track records and reliable bodies of knowledge, such as clinic-trained physicians. A specialist's value is largely based on how rare, consequential, and hard-to-replace that specialist's services are (Tooby and Cosmides 1996), so acculturation linked to newly efficacious alternatives (e.g., clinics) can undermine the high market share that an ethnomedical specialist might have traditionally had, prior to acculturation.

4.3 Limitations

Our study has some important limitations. In study 1, data are based on ethnographic descriptions, so absence of evidence should not be interpreted as evidence of absence. Ethnographers often write about subjects they deem relevant for their own purposes, which did not generally align with our own questions. Moreover, our very critique of the distinction between supernatural vs. natural concepts was linked to a methodological challenge in study 1, i.e., we lacked precise definitional

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principles for interpreting supernatural descriptions. To address this, ADL and CH carefully and independently coded each text record before deliberating about each discrepancy thereafter. (See the SI for coding details.)

In studies 1 and 2, we presented our hypotheses and tests with a working assumption that specialists have high levels of knowledge compared to clients. There is some truth to this assumption, especially where medicinal knowledge is kept secret (Lightner et al. 2021), but expertise is often distributed among multiple specialists with varying levels of knowledge and types of specialization, i.e., a division of cognitive labor (Hutchins 2000; Keil 2003; Heintz 2013). For example, it is unclear whether or not a Maasai participant's group of neighbors and family members, who we interpret as the convenient option, are collectively more knowledgeable about a local illness than a single laibon or local physician. These friends and family were often not explicitly identified by participants in figure 12, and might have even included more "informal" ethnomedical specialists.

Finally, preferences in study 2 were clearly aligned with participants' religious beliefs and trust in religious figures, but the causal direction of these relationships are less clear. Do culturally transmitted beliefs about trusting the laibon and adhering to traditional Maasai religion lead to a preference for the laibon as a healer? Or rather, do these preferences mostly arise from incentives derived from past and beneficial experiences with the laibon resolving practical problems, leading religious commitments to follow? Our findings are consistent with the latter, but the notion that these religious alternatives are solely based on efficacy, rather than norms, prestige, or trust, is a strong claim that our study cannot make. Credibility-enhancing displays, and exploitation more generally, probably play a role in explaining supernatural concepts in ethnomedicine. This broader question about the ideational vs. material nature of culture is pervasive in anthropology (McGee and Warms 2003).

5   Conclusion

This study investigated the extent to which ethnomedical specialists provide "religious" medicinal services to laypersons in traditional, non-Western societies, and why laypersons find such approaches convincing. Using cross-cultural data from the eHRAF (study 1) and field data among Tanzanian

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Maasai pastoralists (study 2), we tested the hypothesis that ethnomedical specialists are "religious" specialists who possess efficacious knowledge about uncommon and serious illnesses. We found that ethnomedical specialists are frequently religious figures who use "supernatural" concepts while fulfilling a practical and specialized service for their clients. Levels of evidence for supernatural theories of disease increased with pathogen stress, proximity to the equator, and lower reliance on market economies, and were more associated with infections and mental illness compared to physical injuries and childbirth. We therefore hypothesize that "religious" beliefs among traditional healers might often, but not always, represent abstract thinking about rare phenomena whose causes are unobservable, rather than a separate "religious" style of thinking. Our cross-cultural data revealed a taxonomy of ethnomedical specialists, suggesting that while some religious figures who assist with medical problems, such as shamans, might be "feared diviners" or "prestigious mentors", many are "efficacious healers" who possess technical knowledge allowing them to exchange efficacious services to clients for various forms of payment.

6 Funding

7 Conflicts of interest/Competing interests

The authors declare none.

8 Availability of data and materials

All data, code, and supplementary materials are available at: https://github.com/alightner/ethno medicine-magic.

9 Author contributions

ADL and EHH designed the study. ADL collected the cross-cultural data. ADL and CH coded the cross-cultural data and collected the field data. ADL and EHH analyzed the data. ADL wrote the first draft of the paper. ADL and EHH wrote the final draft of the paper. All authors read and approved the final draft of the paper.

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Supplementary Information for *Ethnomedical specialists and their supernatural theories of disease*

Aaron D. Lightner, Cynthiann Heckelsmiller, Edward H. Hagen

Contents

1 Supplementary descriptions of the methods in Study 1

Here we provide details about the methods used for the results of the cross-cultural study in the main text, which was based on text records from the electronic Human Relations Area Files (eHRAF).

1.1 Statistical analyses

Our dataset, which comprised a 341 row by 58 column binary matrix of 0's (no evidence) and 1's (evidence for), consisted of text records (rows) nested within authors, who were nested within cultures. To assess levels of evidence for each variable, we determined the proportion of text records with evidence for (text record level evidence) and the proportion of cultures with at least one text record supporting the variable (culture level evidence). To account for the hierarchical structure of the data – some text records came from the same document, and multiple documents reported on the same culture – we fit an intercept-only generalized logistic mixed effects regression model (GLMM) for each binary variable, with random intercepts for authors nested within cultures. The value of the fixed-effect intercept (and its 95% CI) represents the proportion of text records with evidence for a given variable, adjusted for the hierarchical structure of the data. The proportion of cultures with evidence for a given variable was similarly computed, except that its confidence interval was computed with cluster bootstrapping. We then converted each estimated proportion and its CI into percentages, which we reported as the variable's level of support.

To more formally assess and compare the levels of evidence for each hypothesized role of ethnomedical specialists (as efficacious healers, specialists in a market for useful skills, religious figures, and/or prestigious

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mentors), we grouped the variables relevant to each hypothesis and computed a "total score" for each. (We also include "anti-efficacy" and "anti-mentorship" hypotheses because some evidence against their counterparts was available.) The "total score" was the proportion of cells in the data matrix with evidence for each hypothesis. For example, our coding scheme included 6 religious variables, so there was a 341×6 dimension binary matrix for this hypothesis. Of the 2046 cells, 459 (22.4%) had evidence for religious variables. This percentage was the total score, and hypotheses with higher total scores were judged to have more support.

1.1.1 Exploratory analyses of religiosity and the supernatural

To explore religiosity (measured by the total score for religious variables) and the presence/absence of supernatural theories of disease, we used three key techniques.

First, to determine the dimensions of ethnomedical expertise that are associated with religiosity and the supernatural, we fit a poisson regression model with the text record religion scores as the outcome and a logistic regression model with text record supernatural theories (present/absent) as the outcome. In each model, the remaining coded variables on ethnomedical expertise were predictors. Prior to fitting, we removed variables with almost no evidence (>95% zeros) to avoid spuriously large estimates and CI's. Because inclusion of many predictors risks overfitting, we used *elasticnet* regression (Friedman 2021), a popular type of penalized regression that was developed for use in situations where the number of predictors, p is large relative to the number of observations, n. We used the "lasso" penalty, which sets some coefficients to 0, with the non-zero coefficients representing the "best" predictors, given the limitations of the data. (See below for a brief description of the elasticnet regression.)

Second, to determine if continental region and/or mode of subsistence were associated with religiosity and the supernatural among ethnomedical specialists, we fit two separate logistic GLMMs with presence/absence of supernatural theories in each text record as the outcome variable. In one model, continental region of each of the 47 cultures was the predictor variable, and in the other model, subsistence strategy for each of these cultures was the predictor variable. In both models, we included random intercepts for cultures. We then repeated this process using two separate poisson GLMMs, with religion scores in each text record as the outcome variable.

Third, to determine if dimensions of cultures other than their continental region or mode of subsistence were associated with religiosity and supernatural theories of disease, we first compiled all complete quantitative data on 186 cultures from the Standard Cross Cultural Sample (SCCS) from D-PLACE (Kirby et al. 2016) into a dataset. Specifically, we collected all ordinal and continuous variables from the SCCS, and filtered all variables with missing observations. The resulting dataset contained 44 variables with observations for all 186 societies in the SCCS.

We then scaled the entire SCCS data matrix and conducted a principal components analysis (PCA) to reduce the dimensionality of the cross-cultural data. We retained the largest principal components based on variance explained (a scree plot "elbow") and interpretability, along with the principal component values for each culture that was also in our eHRAF dataset of ethnomedical specialists (the *PCs*). Out of the 47 cultures in our eHRAF dataset, 44 cultures were also in the SCCS. We excluded the remaining 3 cultures from this analysis. In a logistic GLMM, we then modeled presence/absence of supernatural theories for each text record as the outcome, culture-level PCs as the predictors, and random intercepts for cultures.

1.1.2 Exploratory analyses of markets and mentorship

To explore the roles of market specialization, efficacy, and mentorship, we used two additional techniques.

First, at the text record level, we weighed the levels of evidence for common incentives for laypersons to patronize ethnomedical specialists (see figure 2 in the main text). In some cases, we also had evidence for corresponding disincentives (e.g., reputation for efficacy vs. reputation for inefficacy); in other cases, we had evidence for contrasting incentives (e.g., assistance with uncommon and serious problems vs. assistance common and everyday problems). To compare the weight of evidence for incentives vs. disincentives, or for contrasting incentives, we used logistic regression to compute the odds ratios of evidence for one vs. the other. Our comparisons were: *specialists conferring benefits* vs. imposing costs; *reputations for efficacy*

vs. reputations for inefficacy; *assistance with uncommon and serious problems* vs. assistance common and everyday problems; *patronage based on efficacy* vs. patronage based on tradition, convenience, or cost (referred to as "socioeconomic" considerations); *evidence of success* vs. evidence of failure; *trustworthy specialists* vs. untrustworthy specialists; and *freely shared services* vs. services for payment.

Second, we assessed which variables were associated with an expansion of the market for ethnomedical specialists. As a proxy for presence/absence of expanding markets, we used the acculturation variable, which usually included presence/absence of foreign hospitals and clinics nearby and, in some cases, ethnomedical specialists from other cultures. Here, we modeled each of our coded variables as the outcome in separate logistic GLMMs, with the acculturation variable as the predictor (i.e., presence/absence of foreign hospitals and clinics nearby and, in some cases, ethnomedical specialists from other cultures) for each model, and authors nested within cultures as random intercepts.

1.1.3 Exploratory analysis of the variables in our data

Finally, to examine structure in our entire data matrix, i.e., to determine which groups of variables tended to have evidence in the same text records and therefore might indicate important abstractions about ethnomedical expertise, we used a network clustering technique known as a minimum spanning tree (MST). We computed the square matrix of all pairwise binary distances between column vectors in our dataset, where a binary distance = 0 means that two variables both had evidence in exactly the same text records, and a binary distance = 1 means that two variables never had evidence in the same text records. The resulting matrix can be conceptualized as an adjacency matrix that defines a weighted graph (G), where each vertex is a variable and each weighted edge is the distance between these variables.

From this we computed the MST, which is a subgraph of G in which every node is connected in a single path, minimizing the total weighted path distance without creating any closed paths (Prim 1957; Dijkstra 1959). In the resulting MST, only similar variables (the vertices) are connected to each other. We then identified "clusters" of variables by visual inspection of the MST, seeking groups of adjacent variables that were conceptually related.

1.2 Explanation of the elasticnet regression model

Here, we briefly describe the elasticnet regression model. Standard regression models are fit by minimizing an objective function. In ordinary least squares regression the objective function is the residual sum of squares (RSS), and in logistic regression it is the negative log-likelihood, $-loglik(\beta)$. Penalized regression models instead minimizes the objective function plus a penalty term based on the magnitude of the coefficient vector. For linear regression this is:

$$\frac{1}{2}RSS/n + \lambda * penalty$$

and for logistic regression:

$$-loglik(\beta)/n + \lambda * penalty$$

There are two popular forms of penalized regression: ridge regression and lasso regression. For ridge regression the penalty is $||\beta||_2^2 = \sum_{j=1}^{p} \beta_j^2$, where the β_j are the regression coefficients, and for lasso regression the penalty is $||\beta||_1 = \sum_{j=1}^{p} |\beta_j|$. When $\lambda = 0$, this reduces to the standard estimation. As $\lambda \to \infty$, the coefficients β_j are "shrunk" to 0. Thus, when λ is small, the βs are relatively unrestricted, which can result in a good fit to the current sample (low bias), but a poor fit on future samples (high variance); roughly, the model will tend to be over-fitted. When λ is large, the βs tend to shrink toward 0, which reduces fit on the

current sample (high bias), but results in a more stable fit across samples (low variance); roughly, the model will tend to be under-fitted. The optimal value of λ is typically found by minimizing cross-validation error.

With the lasso penalty, some coefficients might be set to 0, i.e., dropped from the model, which aids interpretation, but when variables are correlated, the lasso might drop some that are genuinely related to the outcome. In ridge regression, in contrast, the coefficients of correlated variables are shrunk to similar values; although the coefficients of some predictors might be very small, all predictors are retained in the model, which can make interpretation difficult.

Elastic net regression combines the advantages of ridge and lasso penalties using an additional tuning parameter α, $0 \le \alpha \le 1$:

$$penalty = (1 - \alpha)/2||\beta||_2^2 + \alpha||\beta||_1.$$

Thus, $\alpha = 0$ is the ridge penalty and $\alpha = 1$ is the lasso penalty. With intermediate values of α, there is a 'grouping' effect in which strongly correlated variables tend to enter or leave the model together (i.e., have their coefficients set to 0).

In the main text, we used elastic net regression to fit a logistic regression model of each domain type (conceptual, motor, medicine) as functions of our other coded (binary) variables. Following standard procedure, we used 10-fold cross-validation to find the optimum value of λ, i.e., the one that minimized cross-validation error.

1.3 Description of our search query in the eHRAF

In the original Lightner et al. (2021) study, we collected text records from the electronic Human Relations Area Files World Cultures database while intentionally targeting those that reflect some kind of "[ethno]scientific expertise" in the ethnographic literature. Inclusion was therefore based on descriptions of specialized expertise in a potentially relevant conceptual knowledge domains, such as botany, zoology, meteorology, genealogy, traditional history, conflict resolution, wartime strategies, illness, disease, life and death, and physiology. Our exact search query, i.e., the set of OCM codes and search terms that generated our initial results, was:

((Cultures = (Any Culture)) AND (((Subjects = ('173' OR '278' OR '571' OR '577' OR '578' OR '581' OR '582' OR '583' OR '584' OR '751' OR '752' OR '753' OR '757' OR '758' OR '759' OR '761' OR '802' OR '803' OR '804' OR '805' OR '810' OR '811' OR '812' OR '813' OR '814' OR '815' OR '816' OR '820' OR '821' OR '822' OR '823' OR '824' OR '825' OR '826' OR '827' OR '828' OR '829' OR '830' OR '831' OR '832' OR '833' OR '834' OR '835' OR '836' OR '837' OR '838' OR '839' OR '840' OR '841' OR '842' OR '843' OR '844' OR '845' OR '846' OR '847' OR '848' OR '860' OR '861' OR '862' OR '863' OR '864' OR '865' OR '866' OR '867' OR '868' OR '869' OR '875' OR '877')) AND (Text = (knowledgeable OR expert* OR proficient* OR skilled OR specialist* OR practitioner*))))))))

The initial results from the entire eHRAF database found 5734 paragraphs in 1901 documents in 311 cultures, and filtering Probability Sample Files (PSF) found 1595 paragraphs in 483 documents in 60 cultures. ADL read, contextualized, and filtered these remaining 1595 paragraphs to determine whether or not they were appropriate examples of ethnoscientific expertise, i.e., requiring high levels of culturally specific conceptual knowledge about the social and/or natural world. Text records that were included consisted of the focal paragraph from the results, and a contiguous set of paragraphs that provided context necessary for understanding the paragraph that turned up in the results. These are referred to as "text records" in our study.

1.4 Inclusion criteria

The *a priori* justification for including text records was based on whether or not some kind of "[ethno]scientific" expertise was described. We defined scientific domains in this context as conceptual domains where knowledge is ultimately acquired though observation, testing, and/or learning about

natural and/or social principles, which in turn result in developing theories, either over the life course or via cumulative culture, that could potentially be usefully applied to a number of possible types of tasks or applications (e.g., crafts, healing, hunting, trapping, conflict resolution, or ethical quandaries). Crucially, we were searching for knowledge that is not specific to any particular use, but uses might recur because they are relevant to certain types of knowledge. For example, it is unsurprising that plant knowledge (ethnobotany) is frequently relevant to medicine, despite its potential uses in basket weaving. Similarly, animal knowledge (ethnozoology) is useful to hunting and trapping, but might not be limited to these activities alone. In other words, knowledge might be "for something", but what that "something" is was not the topic being queried. Rather, it is high levels of investment in the underlying knowledge (expertise) that were our outcomes of interest.

1.5 Filtering ethnomedical specialists

The protocol described above yielded 547 text records in 55 cultures from a wide variety of domains of ethnoscientific expertise. In our previous study, text records were coded on a large number of knowledge and skill domains (e.g., presence/absence of botanical expertise), with knowledge about medicine as the largest domain of expertise (present in 341 text records). Medicine was also frequently linked to other domains, such as botany, zoology, and healing injuries. To focus specifically on ethnomedical specialists in this study, we filtered the text records in our original dataset to only include those with specialized knowledge about medicine present.

1.6 Complete description of our coding scheme

Each text record was coded by two independent coders (ADL and CH) for each variable in our coding scheme, as described in the main text. Note that some variables in our dataset are evidence against variables in our coding scheme.

Categorical variables are indicated in the descriptions, and were coded as presence/absence for each category as a separate column/variable in our data matrix. This meant that multiple categories could be present in a single text record. For example, if male and female experts were both present in a text record, then we coded presence for both males and females.

Here are our coded variables and a brief description of each:

Text ID: Provides a unique key id number corresponding to a text record, citation, and OCM codes.

Case/model: Does the text record describe a specific case about an expert, a cultural model of expertise, or both? (*Categorical:* Case, model, both)

Age: How old are the experts described? (*Categorical:* Child/adolescent, Adult, Older adult/elderly)

Sex: What is the sex of the experts described? (*Categorical:* Male, female, either/both present)

Costly lifestyle: Does being an expert entail some kind of costly lifestyle, where the expert must fulfill certain obligations on a regular basis, making his/her life substantially more difficult than it would be otherwise?

Costly ritual: When applying his/her expertise (e.g., to perform a service, teaching), does the expert perform some kind of ritual (can be either public or private) in which s/he takes on some kind of cost, e.g., in the form of fitness, money, resources, pain, or risk?

Costly initiation: Does the expert perform some kind of initiation rite, in which s/he takes on some kind of cost (e.g., in the form of fitness, money, resources, pain, or risk) as a condition of being considered an expert by other people?

Expert teaches others: Do experts teach other people what they know? Does becoming an expert entail some kind of apprenticeship, mentorship, assistantship, or knowledge sharing, for example? The expert is described sharing his "know-how" (knowledge or skills) with others, which might or might not be exchanged for something else.

Expert purchases knowledge: Experts conferred a benefit to another expert in exchange for acquiring their knowledge/skill from another person.

Public performance: The expert demonstrates his/her abilities in a public setting, perhaps involving some kind of performance that is visible to others.

Private performance: The expert demonstrates his/her abilities or provides services to others in a private setting.

Experts compete: If multiple experts exist, then they are described as having a competitive relationship with each other.

Experts collaborate: If multiple experts exist, then they are described collaborating or as having a collaborative relationship with each other.

Distributed knowledge among multiple experts: If multiple experts exist, then their expertise is distributed across different roles or types of expertise, which do not strongly overlap with each other.

Hierachy within the domain of expertise: If multiple experts exist, then their expertise involves a hierarchical structure *among the experts* within a given domain, either in seniority among experts or level of skill. (This is not a reference to prestige in the broader community; it is strictly within-domain structure among experts, e.g., senior vs. novice specialists.)

Sexually attractive: The expert is described as being sexually attractive.

Charismatic: The expert is described as being charismatic.

Intelligent: The expert is described as, or has a reputation for being, intelligent.

Multiple mates: The expert has multiple mates.

Deference: People (non-experts or novices) are described as deferring to the expert by displaying signs of respect. (For example, this might include deferring to someone by paying them a respectful greeting, but would *not* include people simply deferring to a medical expert for medical advice.)

Prestige: The expert is considered prestigious, high status, and/or is well-respected in the community. This might include people who are generally paid more attention than others, but is distinct from reputation for efficacy (see below).

Others seek proximity to expert: Is the expert a preferred social partner (e.g., friend, coworker), or frequently/preferentially sought out for advice? Do people (non-experts) seek proximity to the expert, including for reasons that are not directly to the benefits or traditions relating directly to their domain of expertise?

Generosity: Is the expert generous, or does s/he have a reputation for being generous?

Mate fidelity: Does the expert have a mate who gives him/her exclusive sexual access? (Note: this one mostly comes up when violations/evidence against arise. It can include involuntary examples, such as cheating on partners, and voluntary ones, such as wife sharing among experts.)

Reputation as good parent: The expert has a reputation for being a good parent.

Parental investment: The expert is described conferring some kind of benefit to his/her offspring.

Provisions mate: The expert is described conferring some kind of benefit to his/her mate.

Narrow specialization: An expert or experts is/are described as having a narrowly specialized knowledge in their domain of expertise.

Broad generalist: An expert or experts is/are described as having a broad range of general knowledge, such as multiple domains of expertise (e.g., medicine, geography, and meteorology) or multiple unrelated specialties in a domain of expertise (herbal medicine, bone-setting, and childbirth).

Influential outside of area of expertise: The expert has influence over other people in domains outside of his/her domain of expertise. (Examples might include political influence, if the expert's domain is not related to politics, or trusted with medical advice if the expert's domain is not related to medicine.)

Evidence success: Evidence is documented by the ethnographer or his informant describing the expert as applying his/her knowledge or skill for a patron, and successfully bringing about an intended and/or desired outcome.

Evidence of failure: Evidence is documented by the ethnographer or his informant describing the expert as applying his/her knowledge or skill for a patron, but failing to about an intended and/or desired outcome.

Rationalizes failure: If, when applying his/her knowledge or skill for a patron, an expert fails to bring about an intended or desired outcome, s/he rationalizes the event in a self-serving way.

Secretive knowledge: An expert or experts is/are secretive about their knowledge or skills ("know-how"), and attempt to keep it hidden from (e.g., uninitiated) non-experts.

Assists with an uncommon and serious problem: Does the expert have patronage or clientele for their applied knowledge and/or services based on an uncommon and serious problem that arises for the patron (which the expert might be able to help with)?

Receives payment: Does the expert receive money or other material resources (e.g., gift or payment) for his/her applied knowledge and/or services?

Access to mates: Does the expert receive mates or sexual favors for his/her applied knowledge and/or services?

Patronage based on efficacy: Does the expert have patronage or a clientele for their applied knowledge and/or services based on an apparent expectation that the expert will bring about desired and/or beneficial outcomes for the patron? OR Does the expert have patronage or a clientele that is a consequence of the failure of another specialist? (Instead of costs, familiarity, or tradition, for example.)

Patronage based on social/economic considerations: Does the expert have patronage or a clientele for their applied knowledge and/or services based on costs, familiarity, interpersonal trust, and/or tradition?

Cares about reputation: The expert cares about his/her reputation and takes measures to present himself/herself in a positive and self-serving way.

Reputation for efficacy: The expert has a reputation for applying his/her knowledge in a way that can bring about desirable results for other people.

Possesses widely distributed knowledge: While the expert is highly knowledgeable in his/her domain (by definition), other "non-experts" in the community also tend to be fairly knowledgeable in the same domain.

Ornamentation: The expert wears some kind of ornamentation or body alteration that symbolizes to others his/her special status as an expert.

Supernatural: The expert invokes supernatural concepts in his/her theories of disease, appears to use supernatural methods to achieve some outcome, and/or relies on supernaturalistic models of the world to navigate his/her domain of expertise. Supernatural concepts include invisible agents, such as witches or ghosts, or processes that do not conform to the laws of nature.

Religious leader: The expert is described as a religious leader, such as a priest, or holds some kind of significant position/role in a religious group.

Acculturation: Does an expert/ do experts operate in a setting that involves substantial outside cultural contact and blending of new ideas, e.g., from Western cultures?

1.7 Examples of our coded variables

In this section, we include examples of text that would be coded as supportive for each variable in this study. Note that some of these might be multiply coded, i.e., some text records would also constitute evidence for

additional variables, in addition to the variables for which they are illustrative examples.

Supernatural

The co-operation of spirits can be obtained (1) mechanically, through spells, prayers, rites, and sanctified healing waters; or (2) personally and directly, when a debtera forces a demon into his presence and compels his assistance, or when a shaman allows a zar spirit to possess her. The nature of the connection between spirits and numerological instructions, special objects, and astrological-numerological reckonings (a combination especially used in preparing medicaments) is not understood by lay folk. ... Magical directions are specific for each cure and are inherited with it. Any ecclesiastic can annoint sick people with sanctified healing waters. A shaman persuades zar familiars to provide information and influence other sickness-causing zars. Debtera who have special powers can be either "demon-pullers" (ganel sabiy), whose powers come from demon familiars and magic, or minor debtera (tinish debtera), whose powers come from magic only.

Possesses secretive knowledge

The secret language follows the grammatical patterns of standard Trukese, but it is laced with cryptic distortions. Secret words, altered regular words, regular words with special meanings, and esoteric metaphors make this language incomprehensible to those who speak only standard Trukese. Masters of strategy use this language among themselves and in speeches at formal meetings. It is also the medium in which they preserve "significant history" (wuruwo), that is, history that justifies claims to valuables.

Parental investment

Knowledge of this kind is freely applied to the curing of a lineage mate or other close relative as a personal favor. Any one else, however, must pay in advance. The patient brings goods to the specialist and requests his aid. When cured, he is further obligated to the practioner and makes him a present. Such knowledge, then, not only has practical social value, but through its application can provide other forms of wealth for the specialist. To this knowledge, too, the specialist's children and lineage mates have a claim. Without their permission, he may not teach it to another unless he receives compensation for it. For if the specialist teaches someone else, he dissipates the monopoly his heirs will someday enjoy and lowers their future earning power.

Costly initiation

Offers of help soon give way to competition as the established students come to regard him as a rival for the master's personal instruction and encouragement. To be the master's favorite means rapid advancement through the curriculum and a seat at his table. Without his patronship, a student is committed to years of physical misery, scraping to meet his subsistence needs, and paying his "tuition" in arduous and humbling ways, by gathering wood for the master's fire, tilling his garden, and washing the feet of the master and his visitors.

Assists with uncommon/serious problem

The ng'aka, therefore, is employed where a malady or misfortune is caused by something mysterious and inexplicable to ordinary people. He is consulted only on the advice of a diviner though...he may himself be the diviner.

Hierarchy w/in domain of expertise

Most adult men know something about the curing of minor ailments, but very few know how to cure serious illness. There is a graded series of curing techniques and only the most widely known shamans know all of them. Shamans are thus ranked according to their knowledge and abilities. Their powers are founded upon their knowledge of myths. Most adult men know a considerable number of myths but shamans differ from the rest in two respects: first, they know more myths, and secondly, they know and understand the esoteric meaning behind them.

Assists with a common problem

> Wood for building purposes is felled when one comes across a suitable tree in the forest. ... Carpenters keep wood stored at home. Some men are so interested in woodwork that they cannot make any conversation except about wood. An old man in Utsjoki called Tor'te-t seähtsi ("Uncle Spinning Wheel") had gathered so much wood in his home that he could hardly find room enough to sleep in. Boats and sleds require the longest time to prepare, but making a spinning wheel requires the greatest skill. Specialists in making spinning wheels have been known in Utsjoki since at least the middle of the previous century.

Broad generalist

> A few people are experts in several different forms of special knowledge; some know one kind, and some know only fragments of one kind. Although everyone knows that many kinds of special knowledge exists, any particular type is important because few others share it.

Charismatic

> Another reason why the Toradja are set on the treatment with kajoe sina by a Mohammedan is because he combines with his work all sorts of mysterious things, which are impressive. With great ostentation the medical expert pronounces a magic formula over the pot, and if the sick person recovers, then he ascribes this more to the power of this formula than to the effect of the medicine.

Reputation for efficacy

> When a somewhat more complicated disease develops, one has recourse to the known herbal specialists. These specialists...have become known for their general skill or perhaps for success in treating special diseases.

Receives payment

> The patient pays the doctor a fee, usually tobacco and some common article, but one person charges a fee of $5.00 per treatment.

Knowledge domain is not widespread

> There are types of special knowledge relating to medicine and curing, house and canoe construction, navigation, sorcery, divination, and fighting. In general, only older people have special knowledge. ... Not everyone in the older generations possesses special knowledge. It is carefully guarded from outsiders and can only be learned from a close kinsman, or purchased at considerable expense from a non-kinsmen.

Deference

> There are types of special knowledge relating to medicine and curing, house and canoe construction, navigation, sorcery, divination, and fighting. In general, only older people have special knowledge. ... Not everyone in the older generations possesses special knowledge. It is carefully guarded from outsiders and can only be learned from a close kinsman, or purchased at considerable expense from a non-kinsmen.

Knowledge domain is widespread

> Laymen have little difficulty in selecting an appropriate kind of wogeysa , since the ailments treated by each category of wogeysa are characterized by unambiguous syndromes which are easily identified by laymen.

Costly lifestyle

> The agamiy exposes himself to certain dangers in the performance of this therapy. Because he must remove a pathogenic substance through the medium of the sickman's blood, there is the danger that, should any of the blood enter his own mouth, the agamiy may himself fall ill with

the ailment he is treating. In addition, contact with this blood threatens those chronic ailments from which the sickman suffers (such as the rheumatoid pains associated with kitin, syphilis).

Public performances

The wabeno was a highly honoured public official, in a sense, for he was the servant of his community, even though he was entitled to charge a fee for his services. Since his prestige depended partly on his popularity he generally gave a public feast and dance whenever a patient paid for the remedy that dispelled his sickness, or a hunter offered fitting compensation for the medicine that had delivered the game into his hands.

Costly ritual

At intervals in the dances one of the medicine-men might drum and dance alone around the fire, then, stooping, pick up from the embers a hot stone; or he might dip his fingers into a boiling cauldron, extract a piece of meat, and swallow it without evidence of pain. Some Indians say that he derived these powers from the medicines he rubbed on his hands, and that although he neither ate nor drank for four days and four nights previously, his strength remained totally unimpaired.

Knowledge distributed/multiple experts

Knowledge of magic and privileged access to spirits is distributed among four categories of people: herbalists, ecclesiastics, shamans, and debtera. Most herbalists incorporate some magic into their recipes. The rural herbalist is usually a farmer, indistinguishable from his fellows except for his curing. He is known to his public by his ability to treat a specific, named ailment, and his professional title indicates only his disease name specialty and his degree of proficiency, e.g., "expert curer for body ulcers." Few herbalists offer therapies for more than three or four ailments.

Influential outside of area of expertise

Throughout these years, the intellectuals, as literati associated with the court (and often the court itself: some of Thailand's greatest poets and dramatists were kings) helped maintain, develop, and glorify this civilization, but not change it radically.

Evidence of success

Besides the priestess, in each village there are several men and women about whom it is known that for certain indispositions they are familiar with a remedy that has already been applied with success many times. Such a person is then asked to come to try his skill on the sick person.

Evidence of failure

Having two types of medical practice at one's disposal is not always an unmixed blessing, however, since the decision that an illness is natural or supernatural may be, or may be held to be, influenced by external circumstances. A case in point is the following which happened to a very poor family in Hsin Hsing. The parents were no longer young and already had three daughters and a small son when another daughter was born. Before the infant was named (naming takes place on the ninth day and is, in effect, when an infant becomes human) she became quite ill. Instead of calling in a practitioner of Western medicine, which many villagers insisted they would have done first, the family chose to consider the illness supernatural because the baby was not yet nine-days-old. They called in one shaman, and then another. Despite their efforts, the infant died. Under the traditional ideas the death was attributable to the will of the gods, and the family had done all it could do.

Experts collaborate

Every tagañ owns a recipe for an unguent, and the medicaments used in it are kept a professional secret. However, not all tagañs have recipes for kusil prophylaxis. Without the latter, a tagañ who wishes to treat compound fractures must obtain the services of an herbalist whose specialty is the treatment of kusil.

Experts compete

In their social role, midwives felt personal but not group solidarity. A solid bond existed between an older midwife and the particular younger one to whom he or she had given training and magic. … The expert who brought mother and baby through before the deposed midwives glowed inwardly with pride and skill and satisfaction that the magic of his particular teacher had proved effective. The sharpness of the competition reverberated through the words, "I pushed the other midwives down." Community standing or "face" was not lost by an unsuccessful case because of the midwives' fundamental role as helpers only, their faith in their own experiences, and again, the conviction that the course of childbirth was merit-determined.

Reputation for generosity

These first abinet [esoteric skill] are generally gifts from student friends … Among these companions favors are expected to be freely given and no formal accounting is made. Beyond this circle all students are implicitly rivals (towdaderiy). Another source of abinet at this time is some older, more knowledgeable student. Here, the relationship between donor and recipient is framed as an exchange between a patron (radat) and his client (taraj), a customary dyad contrasting power with dependency, and generosity with deference. The new boy appeals that he is abject and threatened by mortal dangers; the donor, by his gift, publicly asserts a status difference which sets him off from novices in general.

Patronage based on efficacy

There is no particular problem with illnesses which can be clearly diagnosed as natural or supernatural. But there are many cases in which the diagnosis is not so easy or clear-cut. Mainly, the villagers rely on past experience to tell them which set of symptoms indicates which category of illness, and thus which kind of practitioner to call in. Naturally, there are considerable variations among the villagers themselves which may predispose a decision in one direction or the other – level of education, amount of experience, financial ability, and even types of social pressure. As one would expect, the actual availability of drugs and doctors affects choice. In recent years the dependence upon Western medicines and Western-oriented doctors has increased as a result of the increased supply of both at relatively low cost. The ease of access to antibiotics and patent medicines, their effectiveness, and the doctors' record of successes have given confidence in Western science, with the result that it is common today for the villagers to turn to Western methods first for most illnesses.

Patronage based on social/economic reasons

Though the poor felt the 20 to 30 baht cost of a midwife was too expensive, and so utilized the free help of a compassionate kinsman (usually the mother) or neighbor, the latter sometimes were as expert manually as a midwife or even on their way to becoming one.

Intelligent

Certain natives, served by a good memory and a livelier intelligence, took an interest in these traditions and legends to the extent of learning those of neighboring families and even of neighboring kingdoms and little by little acquired a reputation as specialists in these matters.

Multiple mates

First, by being a powerful ritual specialist, Roberto had political influence and social prestige in society. Therefore, he could claim a woman in exchange for his ritual services. Secondly, he knew well that Eulalia was the only child of an old, widowed and remarried man in the headwaters area of the Goya stream … Alberto, who indeed cared for Eulalia as for a proper sister, was indebted to Roberto and dependent upon his ritual services. So they could do nothing but accept the marriage. In this way, Roberto took Eulalia as his second wife and became one of the few polygynous men in the territory.

Narrow specialization

Aymara medicine is highly specialízed, and consequently has a great many different categories of practitioners. … It is probably safe to say that no other primitive group known to modern ethnology has such a rich specialization among practitioners of native medicine.

Ornamentation

As soon as possible, the patient's family presents the principal specialist with a string of multi-colored glass beads, which he places around his neck for the ceremony to follow … The multi-colored bead necklaces are frequently worn by snake medicine men even when they are not working on a case, and serve as identity badges.

Prestige

In fishing, especially deep-sea fishing, and in some other crafts, knowledge of the technical processes and of the associated ritual is unequally distributed. … One effect of the possession of such knowledge lacking in others is the opportunity of enlarging one's resources. This is done by resort to fishing banks not commonly known, or use of a special technique at times when the fish refuse all others; or, in the case of a craftsman, by more prompt replacement of his implements, or by gaining goods in payment for his work for others; or to a small extent by the securing of a material return for the imparting of his knowledge to others. Important as an inducement to the acquisition of such personal knowledge, however, is the prestige that it obtains.

Private performances

There is no particular moment that is better than any other for informal conversation about genealogies, except that people are most likely to want to discuss genealogy when they are contemplating a marriage, considering litigation that involves genealogical claims, or asking for financial assistance or political support on grounds of kinship. The conversation usually occurs inside the hut or room of the person whose genealogy is being discussed. The occasion is quite private, and other griots are not likely to attend.

Provisions mate

When, as a result of a different political structure, Ogobara was no longer "canton chief", the village secretary was obliged to look for other occupations. He went to Bandiagara and in the hospital there began a course in male nursing. He lives there in the family house and provides for his two wives and his children who have stayed with Ogobara's family in Sanga.

Mate access for expertise

Most of the bridewealth and other marriage expenses are waived and the girl is given to the husband by those having authority over her marriage dispensation rights … A man may wish to express his gratitude to a mallam for supernatural aid having to do with medicine, prayers, or divination used by the practitioner for the benefit of the group bestowing the girl. In the same way, most individuals having power to bestow a girl would hesitate before refusing the request of a mallam because of the general awe in which he and his supernatural powers are held in the public eye.

Wealthy

The ideal type [of specialist] is a person of respectfulness, bravery, and strong thought who also controls abundant valuables.

Sexually attractive

Some experts may use the DixBo ne [ritual object] on their own account, in which case they become irresistible to all women in the village. Informant mentioned the name of an individual who was an exceedingly successful love expert on his own account.

Others seek proximity to expert

If the professor wants to discourse on the domain of a particular spirit residing in the jungle, he will do so, and on his own time. If he wants to collect medicines one day, the student may follow along. And if he decides to pass on some esoteric information about the plants being gathered – or if he decides not to – that is the way things will happen.

Expert teaches others

When a young Kuna becomes a disciple of an experienced curing specialist he places himself in a thoroughly submissive position with regard to his teacher. Once the branch of knowledge he wishes to learn has been decided upon and fixed, the specialist controls the manner in which instruction proceeds, the sequence in which all knowledge is passed out, and the topics to be discussed during each session … When learning proper begins, the student characteristically listens attentively to a short portion of a chant several times, then is told to repeat it. When he has mastered this task adequately, another piece of the chant is given to him in the same fashion, and he repeats it. On and on it goes until the entire chant has been learned. As the student progresses and demonstrates his capacity for learning he is given information or symbols and their underlying meanings, commentaries on the nature of curing and disease in general, and instruction in accompanying ritual. Such information is conveyed to the student either by demonstration or verbally.

Acculturation

The public health worker is in a position to inherit some of the awe felt for the learned dabtara, especially since the health teams operate out of centers which provide therapy as well as instruction, which gives them the benefit of association with the quasi-magical powers attributed to one who performs successful treatment. In addition, he can be aided by the Amhara peasant's personal devotion to someone who has helped him and won his confidence. Whether this devotion can be stimulated depends, in the last analysis, on the character and resourcefulness of the public health workers themselves. Those who are able to communicate in a dignified manner with the peasants, who avoid dealing with them as an inferior and backward people, who refrain from flaunting the most important local norms, and who are on good terms with local authorities and respected men, have a substantial chance of being accepted after an initial period of suspicion and alienation. Thus it was that a Gojjami peasant, asked why some of the local people were hearkening to the advice of the public health team at Dabra Marqos, explained: "We have come to realize that what you tell us to do is for our own advantage, not yours." Elsewhere in Gojjam, a similar response was the eventual issue of a more pronounced initial rejection of public health workers. In the village of Dajan doors were closed against a venereal disease team which was taking blood samples of the entire population for Kahn test analysis. Popular suspicion was voiced in a number of ways; the health workers were accused of selling blood, of being missionaries, and of otherwise trying to cheat the locals. The health officer in charge of the team then brought some of the objectors to the mobile laboratory, patiently explained what was going on, and how it would benefit the people. Before long word got around that these outsiders were not so evil after all, and the doors of Dajan opened.

In Ceylon, modern medicine whether it is indigenous or Western, has been institutionalized so that there are schools, certificates and centers for the practice of medicine. The village ayurvedic physician who is not associated with the institutions of modern medicine emerges in the hierarchy as a second rung specialist. It is not simply the fact that he is associated with a traditional 'science' and not Western medicine that calls his authority into question. There is general confidence in ayurvedic medicine, and the Ceylon government gives official encouragement to its practice. It is rather that the village specialist either is a successful apprentice to another local practitioner, perhaps to an older, more experienced close relative, or is in some cases even self-taught. His 'science', on the other hand, has become institutionalized along the lines of Western medicine and has adopted some of its practices.

Imposes costs on others

Trobrianders believe in spirits who reside in the bush who cause illness and death but the greatest source of fear is sorcery. Only some people are believed to have the knowledge of spells that will "poison" a person and such experts can be petitioned to exercise their power for others. Counterspells are also known; chemical poisons obtained from elsewhere are thought to be prevalent.

Religious leadership

Treatment of disease and injury [colds, flu] may involve many distinct techniques. There are a great variety of professional medical practitioners such as Western-style doctors, traditional Chinese doctors, various folk specialties such as acupuncture, different shamans, and temple priests who furnish charms to drink.

Learns by revelation

The kusabindugeyu were primarily seers, gifted by their adolescent visions to discern what was normally hidden from human eyes. Most of them claimed to derive their power from thunder, but during the winter months, when thunder had retreated far to the southward (thunderstorms are exceedingly rare in Parry Sound during the winter) they summoned other manidos to aid them in their rites, principally perhaps a small owl (kokoko) and the whip-poor-will (waholi).

1.8 Interrater reliability

Our dataset was coded independently, using the coding scheme described above, by the first author (ADL) and second author (CH) on this study. After the independent coding phase, we checked the interrater reliability and reported these as percentage agreement in our data matrix (85.5%) and Cohen's kappa (0.49) in the main text. An agreement plot visualizes our level of agreement, prior to reconciling the differences in our codes (figure S1). After the independent coding and interrater reliability analysis, ADL and CH went through each disagreement of each text record and agreed on how they should be reconciled.

2 Supplementary results in Study 1

This section outlines additional exploratory results from the cross-cultural study, based on data from the eHRAF and, in a few specified cases, from the SCCS.

2.1 Generalized linear mixed models based on cross-cultural data

We use a generalized logistic mixed model (GLMM) to model our PCA results (PC1: culture complexity and scale; PC2: pathogen stress, proximity to equator, and lower reliance on market economies) as predictors of presence/absence of supernatural theories of disease in the text records, with cultures as random intercepts. We found a "statistically significant" result, in which PC2 was positively associated with supernatural theories of disease, and PC1 was not clearly associated with the supernatural. See table S1.

This result, though interesting, should be viewed with skepticism. PC1 consists of cultural complexity variables, such as urbanization, population size and density, and cash- and market-based economies. PC2 consists of three underlying types of variables: Pathogen stress, proximity to the equator (absolute value of the latitude), and a low reliance on cash and market economies. An explanation that might *seem* compelling, and is consistent with our hypotheses in the paper, is that pathogen stress is a key driver of supernatural theories of disease.

As we state in the main text, however, we can not draw this conclusion based on the association between PC2 and the supernatural, because pathogen stress is confounded by other contributing factors to PC2, such as latitude and cultural complexity. In fact, PC1 and PC2 are sufficiently related that we cannot even draw a firm conclusion about the apparent lack of effect of PC1 on the supernatural.

To see this, notice in table S2 that if pathogen stress is the sole predictor of supernatural, then as we might have expected, we find the weak positive association between pathogen stress and supernatural theories of
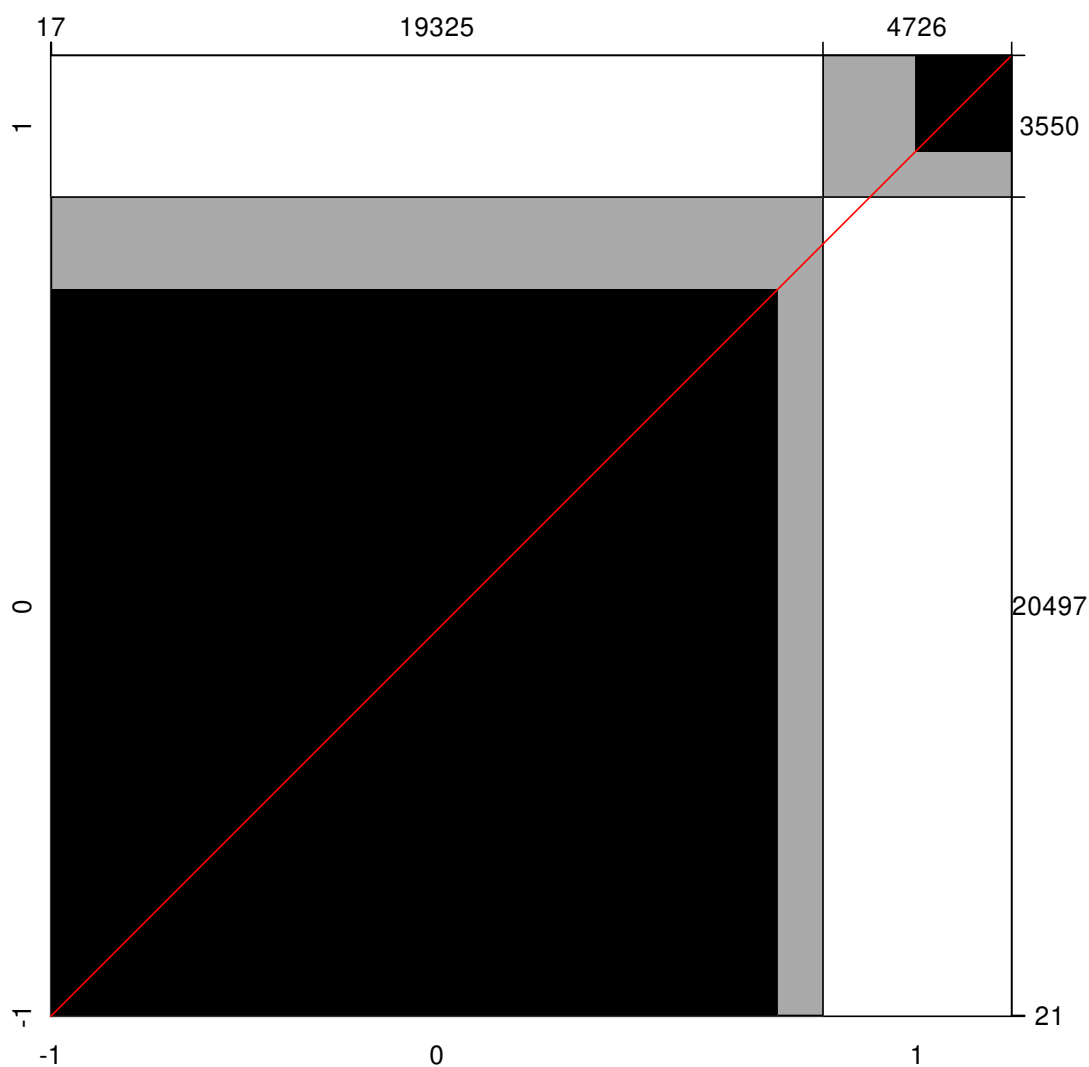
Figure S1: Agreement plot showing the proportions of agreement between the two independent coders (ADL and CH). The dark spaces represent the proportion of agreement for the presence and absence of all aggregated variables in the entire dataset, and the gray spaces represent the proportions of disagreement for presence and absence.

Table S1: Generalized logistic mixed model results for supernatural theories of disease predicted by the first two principal components from a cross-cultural PCA of the SCCS data. Estimates are log odds, with standard error in parentheses.

	Dependent variable:
	supernatural
pc1	−0.03
	(0.04)
	p = 0.53
pc2	0.27
	(0.08)
	p = 0.0003***
Constant	1.11
	(0.14)
	p = 0.00***

Note:	*p<0.05; **p<0.01; ***p<0.001

disease. Adding latitude as a predictor, however, makes the effect of pathogen stress disappear. This is perhaps unsurprising; pathogen stress might be higher in tropical climates than in temperate ones. And yet, further complicating matters, adding PC1 (cultural complexity and scale) thereafter makes PC1 appear to have a significant negative effect on supernatural theories. See table S2.

Table S2: Generalized logistic mixed model results for supernatural theories of disease predicted by the first two principal components from a cross-cultural PCA of the SCCS data. Estimates are log odds, with standard error in parentheses.

	Dependent variable:		
	supernatural		
scale(pathogen_stress)	0.24	−0.01	0.20
	(0.14)	(0.23)	(0.24)
	p = 0.10	p = 0.99	p = 0.42
scale(latitude)		−0.29	−0.37
		(0.22)	(0.22)
		p = 0.19	p = 0.10
scale(pc1)			−0.37
			(0.18)
			p = 0.05*
Constant	1.06	1.07	1.08
	(0.15)	(0.15)	(0.13)
	p = 0.00***	p = 0.00***	p = 0.00***

Note:	*p<0.05; **p<0.01; ***p<0.001

This is not to suggest that our analyses of PC1, PC2, and supernatural theories of disease is completely uninformative (quite the contrary). However, it does suggest that, as we conclude in the main text, confir-

matory research is needed to directly test the hypothesis that pathogen stress is associated with supernatural theories of disease.

3 Supplementary results in Study 2: Maasai field data

This section outlines additional data and results from the Maasai fieldwork study.

3.1 Participant examples of conflict between science and religion

Some Maasai participants ($N = 12$) agreed that scientific ideas sometimes conflict with their beliefs about god or religion. All of these participants were Christians. When asked as a follow-up question to give an example of how this might be the case, some (but not all) participants offered an example. The following quotations are examples of responses that were transcribed during interviews:

> There may sometimes be "satanic emotions" in wise or educated people.

> For example, if doctors say that someone is HIV-positive then they will say that you have to take this medicine and that you might die. The person might start to worry that they will die and have fear because of what the doctor said to them. But the person who believes in god can pray, and it is the prayer, not the medicine, that will make them better.

> Sometimes scientists say there is no god, which I disagree with.

> Science says that there is no god, but we believe differently. The scientists and doctors will not be disturbed by this if they have faith in god also.

> Sometimes I disagree with scientists and teachers if they might say, for example, that there is no god.

> I will sometimes disagree with doctors or scientists if they do not think that god exists or if they are not Christians. But this does not happen if they separate those beliefs with their work.

> My beliefs in god sometimes make me disagree with scientists; unbelievable things in the world are not man-made, but are made by god. Doctors do good things by treating other people though.

3.2 Mosaic plot of preferred specialists for serious illnesses

As we show in the main text, participants overwhelmingly preferred to use the clinic in cases of serious illness, though many also preferred to use either friends, family, or religious specialists. We reported these preferences in the main text by religious identity. Here, we include them in the aggregate to show how strongly the clinic was preferred overall, and how religious options (the church and the laibon) both slightly increased after the first option would hypothetically fail. The clinic was the most popular first option, but as seen in the main text, some participants defaulted initially to family and friends as their first option, but fell back on the clinic as their second option. See figure S2.

3.3 PCA results for explanations of how herbal medicines work

After coding for presence/absence of content features of each participant's explanation of how a common herbal medicine works, we concluded based on visual inspection of the heatmap (figure 14 in the main text) that people were broadly divided into "don't know", "knowing when/how to make the medicine", and and "mechanistic" explanations that use substance and essence terms. We also conducted a PCA on the binary data matrix of these responses. PC1 showed that participants who did not know how the medicine worked, and/or did not have a working model of the mechanisms by which the medicine worked, tended to be associated with explanations invoking the conditions under which a person should prepare the medicine, whereas explanations tended to invoke substances, essences, and physiological terms. See figure S3.

Figure S2: Mosaic plot of the proportions of participants who identified different types of specialists as their first, second, and third choices to help them in the case of having a serious illness. Colors represent categories of responses given by participants in each option.
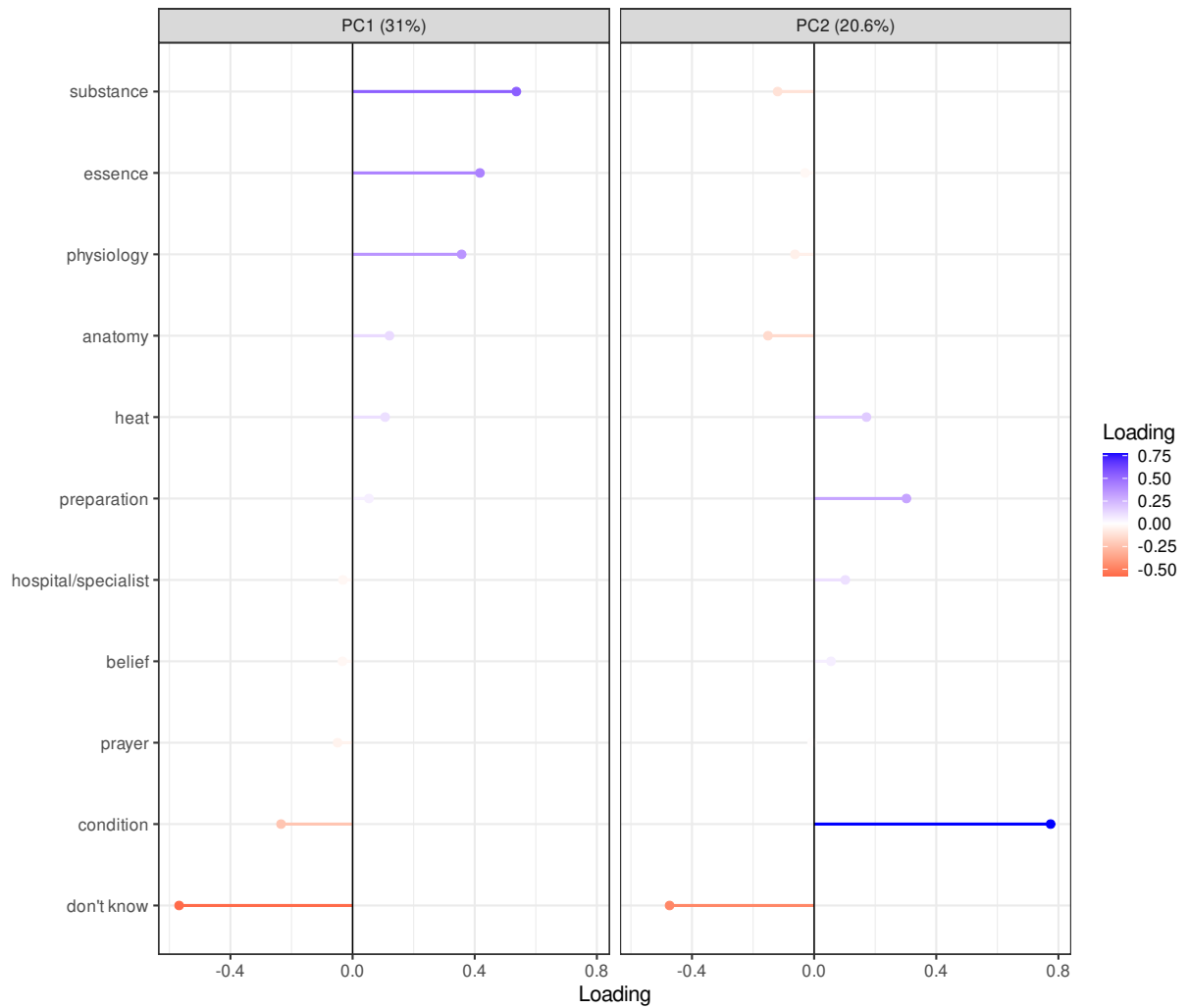
Figure S3: PCA loadings on the first two principal components in the explanations of how herbal medicine works among Maasai participants. PC1 corresponds to knowledgeability and detail of explanation, and PC2 corresponds to the necessary conditions and preparation steps for making the medicine.