The role of causal knowledge in the evolution of traditional technology

Graphical Abstract

Hadza bowyers

Energy storage: reflex > deflex? fraction correct

0 0.2 0.4 0.6 0.8 1

Stored energy

draw length

Highlights

- Among Hadza hunter-gatherers, men construct powerful bows, crucial for their subsistence
- Bow design choices affect energy storage potential
- The evolution of this technology is possible without causal knowledge of key tradeoffs
- There is no statistical evidence that causal knowledge increases with age

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In Brief
Hadza men construct bows from local materials and use these to provide most of the meat in their diet. Harris et al. show these highly skilled bow makers understand some of the mechanical trade-offs associated with bow manufacture, but not others, demonstrating the evolution of a complex technology is possible without complete causal knowledge.
The role of causal knowledge in the evolution of traditional technology

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SUMMARY

Humans occupy a wider range of environments, process more energy, and have greater biomass than any other species because we are able to culturally evolve complex, locally adaptive technologies.1 Competing models make different predictions about the role of causal knowledge in this process. Some argue that innovation and transmission cannot occur without causal understanding,2–5 while others posit that complex technologies can evolve without causal understanding.1,6–10 Prior research on this topic has been restricted to theoretical work and experimental studies with student participants.11–13 The Hadza are foragers who rely on bows for subsistence.14–16 We interviewed skilled Hadza bowyers (bow-makers) and compared their beliefs regarding the tradeoffs in bow construction to those revealed by experimental and engineering research. If bowyers understand the tradeoffs, it is plausible that cultural evolution is rooted in causal understanding, while if they do not, the cultural accumulation of knowledge is likely more important in the process. We show that Hadza bowyers understand some mechanical trade-offs but not others, and therefore the evolution of a complex, highly adaptive technology is possible with incomplete causal knowledge regarding key mechanical trade-offs. Instead, some important design choices made by subjects seem to reflect cultural norms. Although previously published reports have suggested that some individuals are recognized by the Hadza as being especially skilled or knowledgeable,14,17 our results do not indicate that some individuals are significantly more knowledgeable about bow-making than others, nor is there statistical evidence that causal knowledge increases with age.

RESULTS

Following recent thinking in cognitive science,18,19 we define “causal knowledge” as the ability to predict the effect of an intentional modification of a system. For example, bows vary in the cross-sectional profile of their limbs. Hadza bows have a round cross-section, but foragers elsewhere made bows with flattened cross sections.20–22 Changing the cross-sectional shape affects important aspects of bow performance such as energy storage. A bowyer has causal knowledge if he can accurately predict the effects of changing the cross-section. This definition does not require knowledge of modern engineering principles. To have causal knowledge, the bowyer does not need to understand anything about mechanics or material science, just what happens when design changes are made. All else equal, bows with flat cross-sectional limbs store more energy than bows with a round cross section.23 More energy stored translates directly to more range and killing power, desirable features in a bow used for hunting. Of course, many other factors may figure into the choice of bow design—ease of manufacture, availability of raw materials, durability, and so on. A bowyer who knows that a flat cross section leads to more power than a round one might still choose to make a round cross section because the benefits of increased power are less than the costs in terms of, for example, difficulty of manufacture. If this were the case, causal knowledge plus a desire to make a useful bow would explain the choice of bow design. If, however, the bowyer does not know the effects of changing the cross section then the costs and benefits of changing the cross section cannot be balanced against other effects. In this scenario, assuming that range and killing power are important, causal knowledge does not explain bow design and a cultural explanation becomes more plausible. A result such as this should not be interpreted as suggesting the Hadza are anything other than excellent bowyers. It is their prowess in bowery that makes this study possible. Nor would it imply that the Hadza are unusual. In fact, we believe that technology in a diverse range of societies is usually transmitted with only partial causal knowledge.

Individuals possess partial cause-and-effect knowledge

We designed this study to evaluate whether Hadza bowyers have chosen their bow design variant because they understand the
costs and benefits of other designs that are close to their current one. If they do, then one could say cultural evolution is rooted in causal understanding. If not, longer term cultural processes are likely more important. We interviewed 64 highly skilled, active Hadza bowyers regarding important features of their bow. There were 13 questions about bow attributes (Figure 1 and Table S1). Our interview does not address all possible combinations of bow attributes and is not a comprehensive sample of the manufacturing choices available to bowyers. We compare Hadza responses to the “correct” responses as revealed by experimental and engineering research (see Table S2 for detailed description of rationale for interview questions). We provide summary data in the Supplemental information (SI) (see Table S3 for detailed results of interview responses). For each question, we compare the probability of a correct response by chance ($p_c$) to the observed fraction of answers that were correct and its 90% highest probability density region (HPD). If the lower bound of the HPD in an interview question is larger than $p_c$, we say that participants performed better than chance. If the upper bound of the HPD for fraction correct is less than $p_c$, we say that participants performed worse than chance. We also compared the distribution of observed scores to a distribution of 100,000 simulated datasets generated by random guessing. (We used a Monte Carlo approach rather than binomial probabilities to account for the fact that we are missing data for a few questions for some participants.) The observed distribution of scores is significantly different than predicted by chance (Wilcoxon Rank: $V = 21$, $p = 0.036$). Figure 1 shows that the bowyers’ responses were better than chance on 7 of 13 questions, worse than chance on 5 questions, and equal to chance on 1 question. (See the STAR methods for a discussion of the data limitations due to misunderstanding, tacit knowledge, and other factors.)

**Figure 1. Distributions of responses from Design and Mechanical interview questions**

The 90% highest probability density (HPD) interval associated with responses as compared to the probability of a correct response by chance (blue dots) (see Table S1).

There is less causal understanding about design choices than mechanical properties

To refine our understanding of the observed pattern, we performed a post hoc comparison of the interview responses. We partitioned the 13 multiple-choice questions into two categories, Design questions and Mechanical questions (Figure 1). Design questions represent choices made by the bowyer during manufacture that effect the overall shape and appearance of the bow. Mechanical questions refer to factors associated with the manufacture and use of the bow that, although they affect the bow’s energy storage, are independent of a bowyer’s design choices. Study subjects consistently scored higher on Mechanical questions than Design questions (Wilcoxon Rank Test: $V = 219$, $p < 0.001$).

No evidence that some individuals are significantly more knowledgeable than others

To test for the presence of individuals who are more knowledgeable than others, we generated 100,000 random datasets assuming that all subjects have equal causal knowledge and the likelihood of a correct response for each question was the observed fraction of correct of responses for that question. The frequency of observed scores was not significantly different than the frequency of simulated scores (Wilcoxon Rank: $V = 43$, $p = 0.888$, Figure 2; Table S4). There is no evidence that some individuals are more knowledgeable than average but there are two outlier-low scorers, each answering only one question correctly (Figure 2; Table S4). When the analysis was limited to design questions and questions about mechanical properties, the frequency of observed and predicted scores, respectively, was not significantly different (Table S5; Wilcoxon Rank, Design: $V = 19$ $p = 0.73$ Mechanical: $V = 11$, $p = 1$).
We anticipated a positive effect of age on the probability of providing an expected response as bow makers and hunters gained familiarity and experience. However, a Bayesian multilevel logistic regression model indicates there is no detectable effect of age on the probability of a correct response. The posterior point estimate for the fixed effect of age is $-0.0008^{[0.0123, 0.014]}$, indicating no increase in knowledge with age (see also Figure S1). However, if the actual value were at the upper bound of the interval estimate, which the model predicts would occur about 2.5% of the time, the probability of a correct answer would increase by 0.19 with a 60-year increase in age.

**DISCUSSION**

Our results suggest that partial causal knowledge of bowyer mechanics is sufficient for the manufacture and transmission of highly adaptive bow technology among the Hadza. Bowyers are more likely to express beliefs consistent with experimentally verified mechanics when the variable of interest could be learned through experience using a bow. Nearly all participants possessed cause-and-effect knowledge about some mechanical tradeoffs, such as the effect of bow deflex on arrow speed, and they performed better than chance on the majority of mechanical questions. Most participants lacked knowledge of some tradeoffs involved in designing a bow, such as bow profile and cross-sectional shape. For four of the eight Design questions bowyers shared beliefs about bow design that reflect a systematic misunderstanding of cause-and-effect knowledge, and for one of the remaining four Design questions, the percent correct was not significantly different from chance. This difference may be a product of our sample of interview questions.

Hadza bowyers consistently expressed beliefs about limb cross section that diverge from what is known about bow mechanics (Figure 1 and Table S1: Questions 5 and 6). By varying the shape of a bow’s cross section, a bowyer can control several of a bow’s properties, such as the mass of the bow and its draw weight. Experimental studies in bowyer mechanics indicate that limbs that are flatter and more rectangular are considerably more energy efficient than other designs. Despite being aware of other design options, the round cross-sectioned bow dominates among Hadza bowyers. Most bowyers indicated that any deviation from a bow with the round cross section would result in a deleterious outcome. This, in turn, suggests that Hadza bowyers’ choice of cross-section shape is not the result of a causal understanding of the efficiency of alternative shapes. Study participants were asked why they believed a round cross sectional shape to be best and 53% indicated that “it is the Hadza way,” 32% stated that “this is the way the elders have instructed us,” 10% expressed knowing through experience, and 5% stated that, although they believed round to be better, they did not have an explanation. This would suggest that a culturally provided design dominates this aspect of their bow, rather than an understanding of how cross section shape affects bow performance.

Bow profile provides a second example of incomplete understanding of bow mechanics and the role of cultural learning. Design questions 1 and 8 (Figure 1 and Table S1) asked bowyers to relate bow profile shape and arrow speed. Question 1 asked bowyers to rank a series of three bows differing only in their degree of deflex ranging from a near-straight profile to fully deflexed (Figure 3A). 86% of subjects reported a belief that is consistent with the known relationship between deflex and energy storage potential. Question 8 asked bowyers the same question except now bowyers were asked to assay a straight, reflexed (or recurved), and deflexed bow (Figure 3B). Even though 83% of those interviewed reported familiarity with the more energy-efficient recurved design, only 3% of subjects identified it as possessing greater energy storage potential. The difference between these two questions suggests that Hadza
b bowyers possess partial cause-and-effect knowledge concerning bow profile. Hadza bows typically exhibit a deflexed profile, and most Hadza bowyers correctly predicted how changes in amount of deflex affect energy storage. However, when the bow variant deviates beyond the deflexed profile and becomes reflexed, nearly all study participants rejected the design as being inferior despite being familiar with the design characteristic. Hadza bowyers frequently alter the profile of their bows using heat, water, and wax, and thus could reflex a bow’s limbs. However, this design variant appears to be outside the Hadza-bow paradigm. The transition from a straight profile to a slightly reflexed profile represents a relatively small shift in design, but among Hadza bowyers this shift is almost universally viewed as being deleterious. This suggest that their decision not to construct reflexed bows is a culturally derived choice, not the result of causal understanding.

Hadza bowyers manufacture finely crafted, high-performance bows capable of killing a wide variety of prey using materials available in the local environment. There are many tradeoffs in bow design, and we measured knowledge relevant to only a few of them. A round cross-section could be better because materials are more readily available, it is easier to manufacture, it is more durable, it is less likely to fail, or because of other factors currently unknown to us. The fact that the Hadza do not understand some tradeoffs does not imply that their bows are suboptimal. A bow with a rectangular cross-section or a reflexed profile might generate more arrow speed but be too time consuming to make or too fragile. In the current study, we do not address whether Hadza bows are optimal. Given that they are highly successful hunters, we would be inclined to copy the Hadza if we needed to manufacture a bow using local materials in Hadzalnd. More generally, it is a mistake to think that individual calculations based on causal understanding must yield better solutions than cultural learning. Individual learning and calculation can be costly and error prone, and it may often be better to adopt the solutions arrived at by your culture over time. There is much theory that suggests that this is possible, 36 and it is this conviction that stands behind the hypothesis that it is cumulative cultural evolution that has allowed our species to be so successful over the last 50,000 years.

Our results also suggest that socially acknowledged skill is not associated with exceptional causal knowledge. Prior writers have noted that some Hadza individuals have socially acknowledged skill in areas such as hunting, honey gathering, and arrow making [14,193, 17,268]. These reports are based on nominations by other camp members. Our results suggest that although specific individuals within the population are perceived as more skilled bowyers, this ranking does not coincide with greater causal knowledge as measured here. In other words, bow-making skill as perceived by Hadza bowyers does not appear to be predicated on exceptional cause-and-effect knowledge of bow mechanics. Although we did not find evidence for exceptionally high scorers, we did find evidence for two low-scoring individuals, suggesting there are differences among individuals in their likelihood of answering the questions correctly.

We found no significant effect of age on causal knowledge. A variety of models of individual learning predict that accumulated experience will allow learners to learn causal relationships. 34,35,37 Consistent with this view, a number of studies show a central tendency for foraging skills to increase with age. 38–40 Importantly, in the current study we evaluate cause-and-effect knowledge, not the skill required to manufacture a bow. It is possible that bow making skill does increase over the age range of participants, but causal knowledge about bow making does not. It is also possible that essential bow making knowledge is culturally learned in middle childhood, a range of ages not included in our sample. Data on skill learning from Fiji 31 are consistent with this hypothesis. Finally, it is possible that this result is due to lack of statistical power. If the effect of age were at the upper bound of the 95% interval for the fixed effect of age, then older bowyers would have substantially better causal knowledge than younger bowyers.

There is limited formal pedagogy among the Hadza, 14 although Hadza children recently have been observed engaging in a range of verbal exchanges that correspond with some definitions of teaching. 32 The children’s verbal exchanges are all informal and often occur in the context of play or other group
activities in which verbal instructions serve multiple purposes, including coordinating joint action. In the absence of formal pedagogy, observational learning is subject to causal and teleological opacity. Although this problem can be mitigated through trial-and-error learning, it requires considerable time investment and may ultimately be unsuccessful. Until now, it has been unknown whether the transfer of technological knowledge included associated causal information.

This paper has shed light on the degree to which conventional design choices are based on causal knowledge of bow mechanics. Our findings indicate that the evolution of complex technologies, such as the bow, can occur with only partial causal understanding. If expert-level causal understanding isn’t necessary for cumulative culture in extant humans, then we should not infer from the existence of complex, cumulatively evolved artifacts that other hominins had exceptional cognitive abilities. In other words, causal reasoning alone is not the secret to our success. This study provides a clear case of how culturally acquired beliefs affect technological choices. A holistic understanding of technological evolution should not discount the role of cultural conventions or our species’ exceptional, culturally augmented cognitive abilities.

STAR METHODS

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SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.cub.2021.01.096.

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AUTHOR CONTRIBUTIONS

J.A.H., B.M.W., and R.B. designed the research. J.A.H. and B.M.W performed the research, J.A.H., B.M.W., and R.B. analyzed the data and wrote the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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REFERENCES

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KEY RESOURCES TABLE

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RESOURCE AVAILABILITY

Lead Contact and Materials Availability
Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Jacob Harris (jacobharris1809@gmail.com). This study did not generate new unique reagents.

Data and Code Availability
The datasets and codes supporting the current study have not been deposited in a public repository because these are part of further investigation, but they are available from the corresponding author upon reasonable request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

In 2017 and 2018 we interviewed 64 active Hadza bowyers from six different camps between the ages of 13 and 75 years old (mean = 40.03, standard deviation = 14.95) regarding bow manufacture and use. All study participants were male. All interviews were conducted privately, and the participants’ responses were kept confidential. Permission to conduct research in Tanzania was received from the Tanzanian Commission for Science and Technology (COSTECH). All consent procedures and research protocols were approved by the Arizona State University Internal Review Board (IRB) and the University of California, Los Angeles IRB. Camp and individual consent was obtained prior to all data collection.

METHOD DETAILS

In the current study we examine the importance and nature of cause-and-effect knowledge in the manufacturing of one of the most significant technologies in human evolution – the bow and arrow. The Hadza of northern Tanzania are proficient bow makers and have been practicing the craft for many generations. Thus, the Hadza provide a unique opportunity to study the importance of causal knowledge within this valuable context. However, it is important to recognize the Hadza are not culturally isolated, nor are they unchanging in their technological choices. With changing environments and increased contact with pastoralist groups, agriculturists, and even researchers, Hadza continue to modify their behavior and their technology. Thus, it is crucial that Hadza not be considered “living fossils“.

Indeed, Hadza material culture has undergone observable change over time and in fact, since 2016, a new form of projectile point has emerged and is growing in use (Wood and Harris, Unpublished data). One of the key values of this study is that it represents the first step in a large-scale longitudinal study of Hadza technological evolution.

Study Population
The Hadza are hunter-gatherers living in a semi-arid savannah region of northern Tanzania near lake Eyasi. While the Hadza are not isolated from cash economies, and some Hadza go to school, experimental work by Blurton Jones and Marlowe’s show no reduction in measured foraging skills owing to years of schooling. Thus, bow manufacture and hunting continue to play a crucial role in the daily subsistence of those included in the current study. In recent years access to domestic foods such as corn and millet has become more widespread. However, Hadza men still provide most of the protein and lipids in their diet by hunting game using bows and arrows. Over 95% of Hadza men possess and regularly use bows and arrows (Wood, unpublished data). Hadza men frequently manufacture new bows, occasionally manufacturing several bows in a year. Over the course of a lifetime a Hadza hunter will likely use and manufacture well over 100 bows.
Interview Procedure

The primary interview consisted of 13 questions designed to assess the degree to which individual bowyers’ beliefs concerning the mechanical properties of bows correlates with experimentally known principles of bowyer mechanics (Figure 1 and Table S1). Bows can vary in many dimensions, including length, limb width, limb thickness, limb cross section, degree of limb taper, crown height, and profile shape. The current study represents an initial examination of Hadza bowyer knowledge and addresses a few of these dimensions. For each interview question, it was explained to subjects that only the feature of interest was being varied and that all other features of the bow were being held constant. These questions covered basic bowyer mechanical relationships, and questions had an answer coded by the authors as “correct,” i.e., the expected response based on experimentally known principles of bowyer mechanics (see SI Table S2). For each question, either arrow speed or noise reduction was of primary interest. In our assessment of causal knowledge, we recognize it is also possible (though unlikely), that subjects might possess implicit causal knowledge that our interview did not detect.

The interviews were administered in Kiswahili and Hadzane with the help of a research assistant fluent in English, Kiswahili, and Hadzane and were performed in a private location away from other camp members. When administering the interview, a combination of images as well as the participant’s own bow were used to assist in describing the variable of interest. Prior to administering the interview, the first author and the research assistant discussed each question and all relevant variables at great length to ensure the assistant was well versed in all concepts covered in the interview. This ensured the accurate conveyance of information to the study participants. The interview questions (Table S1) represent the general template used. However, on occasion it was necessary to expand into more detail regarding the concept of interest to ensure the information was being accurately conveyed and that the subject fully understood the what was being asked (see Study Limitations).

There are inherent, well-known difficulties associated with interview-based study methods.53 To mitigate some of the more common issues, such as language barriers, an experienced and trusted translator fluent in English, Kiswahili, and Hadzane was employed. The translator was well-briefed on the interview and all concepts therein prior to administering the interview. To minimize interviewee fatigue, interview length per subject was modest. Hadza subjects are accustomed to participating in much longer interviews than that associated with the current study. As a component of our larger research studies, we regularly engage in long interviews at the close of each period of data collection in a camp, gathering a variety of demographic and social data. These interviews are typically longer than the 13-question interview regarding bowyer mechanics.

Study Limitations

Although many precautions were taken to ensure the rigor of the study methods, it is important to acknowledge the limitations. Precautions were taken to avoid language barriers, but it is nearly impossible to eliminate these completely. During the interview, if the interviewee required additional clarification, this was administered with the assistance of the translator. By not rigidly adhering to the interview form, we ensured the subject fully understood the question being asked, thus ensuring the fidelity of the responses. However, it is possible that different degrees of explanation could potentially affect the responses. Another limitation is the possibility that not all study participants were as experienced in verbal causal reasoning as people from WEIRD populations. There is the possibility that some people may possess implicit causal knowledge that our interview was not able to detect. Finally, the current study addressed a subset of bowyer mechanical tradeoffs and therefore does not represent all possible causally important manufacturing decision faced by a bowyer.

QUANTIFICATION AND STATISTICAL ANALYSIS

We estimated the probability of observed scores under the null hypothesis - guessing for each question and arriving at the correct response by chance. To calculate the probability of correct responses by chance, we used a Monte Carlo approach rather than binomial probabilities to account for the fact that we are missing data for a few questions for some participants. This was done for all scored interview questions and repeated 100,000 times to generate 100,000 simulated datasets. We chose 100,000 in order to be computationally straightforward. To account for some missing values in the observed data, we incorporated random missing data into the simulated datasets at the same proportion observed in the raw data. We then calculated the cumulative distribution function (CDF) for all simulated responses as well as each category, Design and Mechanical. From the CDFs we calculated the frequency of scores expected by chance alone and compared to the observed frequency of scores. We also calculated the degree to which participants did better, worse, or the same as chance for each multiple-choice question by comparing the 90% highest probability density (HPD) interval associated with the observed responses to the probability of a correct response under the null. Bayesian HPD intervals were calculated using the R package ‘binom’54.

The probability of achieving the observed scores was estimated by generating simulated data using the distributions of observed responses. Thus, rather than estimate the probability of score given the null, we calculate the probability of score given the observed probabilities associated with each multiple-choice question. Given the observed distribution of scores therefore, this analysis asks; what is the probability of getting a dataset that looks like the observed? We generated 100,000 simulated datasets to produce distributions of scores at specific intervals (e.g., 0 ≤ x < 1/13, 1/13 ≤ x < 2/13, etc.), making it possible to calculate the probability of scoring into the respective ranges. These probabilities were used to calculate the expected frequency of score at each interval. We
replicated this analysis by randomly shuffling our observed data and then calculating the probability of scoring into the respective intervals, as above. The results of the two analyses yielded almost identical results. The R package ‘dplyr’ was used to facilitate analyses.55

For post hoc analyses, we partitioned the interview questions into two categories in order to identify patterns of bowyer knowledge possessed by Hadza; Mechanical and Design. Both categories of question are directly related to the energy storage potential of the bow, and the tradeoffs in each category are governed by mechanical principles associated with bowyer technology. The categories differ, however, in that Design questions represent specific choices made by the bowyer that effect the overall shape and appearance of the bow. Design variables such as bow profile (i.e., side-view shape) or bow length represent choices made by the bowyer that not only affect the energy storage potential and performance of the bow, but also directly affect the overall shape and appearance of the bow. In contrast, Mechanical questions refer to the subset that involve factors or metrics associated with the bow that, although affect the energy storage potential, are independent of a bowyer’s specific design choices.

To assess the effect of age on the probability of providing an expected response, we used Bayesian multilevel logistic regression models using fixed and random effects to estimate the probability of answering questions correctly. Age is treated as a fixed effect and person, question, question category, and camp membership are treated as grouping variables to allow for the examination of the random effect on individual responses. To accommodate different samples associated with the groups of interest, variables treated as random effects are partially pooled, allowing for the sharing of information across groups.56 We implemented our model using the R package ‘brms’57.