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POPULATION SIZE DOES NOT PREDICT ARTIFACT COMPLEXITY: ANALYSIS OF DATA FROM TASMANIA, ARCTIC HUNTER-GATHERERS, AND OCEANIA FISHING GROUPS

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A mathematical model purporting to demonstrate that the interaction population size of a group of social learners is a primary determinant of the level of technological complexity achieved by the members of that group through imitation of the most skilled individual in the group has been proposed. Empirical validation of the model has been attempted with archaeological data from Tasmanian hunter-gatherers and ethnographic fishing data from Oceania, but these data do not support the model. Data from a wide variety of hunter-gatherer groups show, instead, that implement complexity varies with an interaction effect between risk and number of annual moves and not with the interaction population size. Data from the Polar (Inuit) Eskimo and the Angmaksalik Inuit on the east coast of Greenland show that complex implements were part of both group's technological repertoire even though each had interaction population sizes limited to a few hundred individuals, in direct contradiction with predictions from the mathematical model. The problem with the model lies in an invalid assumption.

Introduction¹

Several recent papers ([1- 4]) have advanced the intriguing argument that the size of a population of “interacting social learners” who form a “*well connected* cultural population” [p. 202 in 1, emphasis added], whether co-residing or not, is an independent, causal factor affecting the technological variety and complexity of human produced artifacts. (Henceforth we will refer to the population of interacting social learners as the *interaction population*.²) Supposedly, the variety and complexity of artifacts is a consequence of the interaction population size, keeping fixed the mode of adaptation [1, 4]. As an application of this argument, Adam Powell and coworkers [3] have suggested that the florescence in the variety and complexity of stone tools in the European Upper Paleolithic may simply be a population-size driven phenomenon and so there is no need to hypothesize genetic changes in the cognitive abilities of ancestral *Homo sapiens* for this florescence. Similarly, Michelle Kline and Robert Boyd [4] have argued that variation in the complexity of fishing implements among island groups in Oceania is due to variation in their interaction population sizes, with the latter measured by degree of contact among island groups. In the reverse direction, decrease in the interaction population size could lead, it is argued, to maladaptive reduction in tool complexity. Tasmania, with archaeologically documented disappearance around 4,000 *ya* of the bone points that the inhabitants of Tasmania had previously been making and most likely were using for the manufacture of clothing [5], has been offered as an example of maladaptive reduction of tool complexity [1].

Though an intriguing argument, it is flawed both theoretically and empirically. The mathematical model used to relate

change in complexity to the interaction population size depends upon an invalid assumption without which the claimed relationship disappears. The two empirical examples that supposedly demonstrate the model in action are contradicted by the facts of the Tasmania and the Oceania data. In addition, extensive data on hunter-gatherer implement complexity, environmental conditions, and interaction population size unequivocally demonstrate that there is no relationship between tool complexity and interaction population size. Instead, more than 97% of the variability in implement complexity among hunter-gatherer groups from tropical to temperate to Arctic environmental conditions can be accounted for by an interaction effect between risk and number of annual moves when differentiation of hunter-gatherer societies into foragers and collectors [6] is also taken into account [7].

The model for tool complexity driven by the interaction population size implies that the average skill level for tasks performed by the members of a group after imitating a target, skilled individual will vary monotonically with the interaction population size [1]. In this model, the expected mean skill level among the imitators after imitating the artifact produced by the most skilled person in the interaction population is given by $\bar{z} = E[z_h] - \alpha + \bar{e}$, where z is the achieved skill level of an imitator after imitation has taken place, $E[z_h]$ is the expected skill level in the group for the most skilled individual h , α is the imitation bias (measured as the difference between the skill level for tasks done by the target person being imitated and the modal skill level of imitators after imitation has taken place) common to all imitators due to imperfect imitation, and e is an individual specific error term assumed to come from a (fixed) Gumbel

(α, β) distribution with mode α and spread β . Next, it is assumed that individual skills have a Gumbel (α, β) distribution and so $E[z_h] = \alpha + \beta(\varepsilon + \log N)$, where α is the location parameter (modal value) for the assumed Gumbel distribution of individual skills and ε is the Euler-Gamma constant ($\varepsilon \approx 0.577$).³ From this and the Price Equation [9], it follows [1] that $\Delta \bar{z} = -\alpha + \beta(\varepsilon + \log N)$.⁴

At this point, the model uses a crucial, unstated assumption. It is implicitly assumed that the imitation bias, α , remains constant even after there has been change in the skill level of the target task for the imitators. Under this assumption and the fact that the expected value of the most skilled person in an interaction population with skills distributed according to a Gumbel distribution is proportional to $\log N$, it immediately follows that \bar{z} varies monotonically with $\log N$. From this relationship it may be concluded that the interaction population size, N , will be a driver for the complexity of artifacts produced by the members of a group.

However, assuming constant α when there is change in the interaction population size, hence change in the target skill level of the most skilled person in the interaction population, contradicts the statement: “If something is easy to imitate [then] $\alpha \dots$ will be small. If something is hard to imitate \dots then α will be large” [p. 201 in 1]. This statement makes intuitive sense. Recall that α measures the difference between the average skill level expressed in what the imitators actually achieve in comparison to the skill level required for the target task. If the imitators have never made a pot, they are likely to have small α if they imitate a potter making a simple pot but large α if they imitate a highly skilled potter making a complex pot. Individuals do not increase their maximum skill

level merely by imitating a task that requires still greater skills.

According to the above quote, α will vary monotonically with the interaction population size since the (expected) skill level of the target person varies monotonically with the interaction population size. If so, would not the change in α due to change in the skill level for the target task simply balance out any change in skill level of the most skilled person when the interaction population size changes? We can answer this question as follows.

The model assumes that when the i th, randomly selected imitator from the interaction population of imitators imitates a task being done by target person h who has skill level, z_h , the imitator will end up with skill level $z_i = (z_h - \alpha) + e_i$, e_i a value drawn randomly from a Gumbel (α, β) distribution of error terms. Though not stated explicitly, presumably the most skilled person is doing the most skilled task s(he) can do given her or his level of skill and each imitator is also doing as well as s(he) can.⁵ (While not critical here, the model allows for the possibility that an imitator may be able to do a more skilled task through imitation than he or she could do without imitation.)

Assume, for convenience and without loss of generality, that the interaction population is in equilibrium, so $\Delta \bar{z} = 0$. Suppose a migrant k with skill level $z_k > z_h$ now joins the interaction population and does a task requiring his or her higher skill level z_k . This task becomes the new target under the assumption that the target for the imitators is the task requiring the highest skill level [p. 200 in 1]. With the implicit assumption of constant α , the new average skill level in the interaction population will be $\bar{z}^* > \bar{z}$ merely because a task requiring a higher skill level is now being imitated by the same interaction population of

imitators.⁶ For this to be the case, the maximum skill level each imitator can achieve must somehow increase simply because of imitating a higher-skilled target.⁷ That makes no sense and contradicts the statement about α varying with the skill level expressed in the target. The maximum skill level that each imitator can achieve does not increase merely because a target requiring a yet higher skill level is being imitated. If that were the case, then the achieved skill level of the imitators could be made as high as one wanted simply by changing to a target requiring a correspondingly high skill level for its production. Instead, if each imitator is already doing as well as he or she can, then the skill level achieved by the i th imitator after imitating the new, harder to imitate target will be unchanged.

To put it another way, consider for simplicity and without loss of generality the case where $\alpha = 0$ and so, according to the model, $\Delta \bar{z} > 0$ regardless of the population size, N . Assume the population of imitators is fixed and let “generation” in the model refer to a round of imitation by the population of imitators of the most skilled individual in the population in that round of imitation. Thus the same population of imitators engages in multiple rounds of imitation, as might occur if, say, artifact production occurs once a week. After the n th round of imitation, the population of imitators has increased its average skill level by the amount $n (\Delta \bar{z})$ and so the skill level of all imitators must increase without limit as the number of rounds of imitation increases since the model assumes the spread in skill levels in the population of imitators is fixed. This implies that the skill level that can be achieved by each individual in the population of imitators will increase indefinitely simply through repeated rounds

of imitating the most skilled person in the population, which does not make sense. The problem lies in the assumption that α is fixed regardless of the skill level of the target.

Instead of an achieved skill level based on fixed α on the part of the imitators even when there is change in the skill level of the target person due to changing from person h to person k with greater skills as the target person, the expected skill level for the imitators should be $E[z_i] = (z_k - \alpha_k) + \bar{e}$, where α_k is the imitation bias for the imitators when imitating person k doing a task requiring skill level z_k . For the expected skill level of the imitators to remain unchanged (that is, assuming the imitators have already reached their maximum skill level), $(z_h - \alpha) + \bar{e} = E[z_i] = (z_k - \alpha_k) + \bar{e}$ and so $\alpha_k = z_k - (z_h - \alpha) = \alpha + (z_k - z_h) > \alpha$, where α is the imitation bias when imitating the maximally skilled person in the population with skill level given by z_h . Thus the imitation bias increases by the change in the skill level of the target. This agrees with the above quote about the imitation bias varying monotonically with the skill level of the task being imitated.

Whether the change in skill level when going from target person h to person k is due to person k migrating into the group or is due to change in the interaction population size does not affect the argument. The role of changing the interaction population size in the model is simply to allow for change in the skill level of the most skilled individual in the interaction population. Thus the change in α when going from person h to person k as the target for imitation due to the increase in the interaction population size will precisely match the change in skill level of the most skilled individual and so there will be no change in the average skill level of the imitators.

The same conclusion applies to the Powell and coworker simulation [3] in which they relax the assumption of imitating the most skilled individual. In their simulation, the interaction population is divided into subunits with migration occurring among them and a migrant is a target for imitation only if the migrant is more skilled than any other possible target within the subunit, such as the parent of an offspring. They still find that the average skill level changes monotonically with the interaction population size, though only because they are using the same model for change in skill levels of the imitators and so they also assume constant α . While it is useful to demonstrate that the conclusions reached by Henrich can be extended to the more realistic situation modeled in their simulation, the results obtained in their simulation still depend on the erroneous assumption of constant α .

In the Results section I first consider the Tasmanian data set that was claimed to support the model and argue that the simplest explanation for the loss of bone points is change in climatic conditions eliminating the need for clothing whose production required bone points. Then I discuss the strong relationship between complexity of artifacts and an interaction effect between risk and number of moves in hunter-gatherer groups. Next I consider the two hunter-gatherer groups, the Polar (Inuit) Eskimo and the Angmaksalik Inuit of eastern Greenland, for whom data on the interaction population sizes are available. In both cases, I find that the model is contradicted by the data on the interaction population size and the complexity of tools. This is consistent with the finding that the complexity of tools varies with the interaction effect between risk and number of annual moves and not with population size or population density as proxy measures for the interaction

population size. In addition, the claim that the interaction population size for the Tasmanians was on the order of 8,000 persons when they were making bone points leads to implausibly large estimates for the interaction population size that would be needed to account for the complexity of the Inuit tools.

Finally, I reexamine the analysis of the data from ethnographic reports on subsistence fishing groups in Oceania that purportedly show fishing implement complexity varying with the interaction population size. The authors of that analysis correctly require that all groups in their data set should have the same economy and ecology, in this case a subsistence fishing economy. However, review of the groups included in their data set show that one group, Hawaii, deviated from the other groups by having a well-developed barter economy based on mixed land and sea farming. Statistically, Hawaii is also an outlier for the linear relationship between the population size and number of types of tools found for these data. Reanalysis of the Oceania data with Hawaii excluded does not lead to an attenuated pattern as would be expected if all the data points fit the pattern observed when Hawaii is in the data set. Instead, the claimed relationship between the interaction population size and complexity of fishing implements does not hold when Hawaii is excluded from the data set. Rather, the complexity of their implements appears to vary with risk, in agreement with what has already been documented for hunter-gatherer societies.

All told, these analyses show that the model for relating tool complexity to the interaction population size is not empirically supported. The model for relating artifact complexity to the interaction population size of social learners is flawed internally by an

invalid assumption and externally by lack of fit with relevant data.

Methods

Tasmania

Published archaeological reports, articles and books are used to provide data on the nature of clothing in prehistoric Tasmania, on changes in climate from the Pleistocene to the Holocene, on archaeological sites where bone implements were found and on the dating of these sites. As with archaeological data in general, it needs to be remembered that “absence of evidence is not necessarily evidence of absence.” Absence of bone points during some time periods need not mean they were not made and used in those time periods.

Undocumented claims about the complexity of the bone points as implements have been assessed by considering line drawings of them. The results derived from extensive analysis of data on variation in the complexity of implements and their patterning presented in [7] are used to disprove the commonly made assertion that the Tasmanians had an anomalously simple tool kit in comparison to other hunter-gatherer groups.⁸

Complex Tools Among Hunter-Gatherer Groups

Previous work showing that risk is a major determinant of the complexity of implements among hunter-gatherer groups is reviewed. The complexity of tool design is measured through the number of ‘technounits’ [TU] per implement, where a TU was defined by Wendell Oswalt as “an integrated, physically distinct and unique structural configuration that contributes to the form of a finished artefact” [p. 38 in 14]. The number of TUs relates to the likelihood of killing an animal once it is detected. For example, a bow and arrow with its multiple parts gives

more control over the flight path and kinetic energy of an arrow in comparison to a spear having a single part and thrust by hand. Hence the arrow is more likely to strike and kill an animal at a distance than is a spear.

The rationale for using population density as a proxy measure of the interaction size of a population of social learners is considered. Current demographic data from northern Canada are used to estimate the geographical area that would be necessary for the Inuit to have had an interaction population size comparable to that claimed for the Tasmanians, taking into account the far more complex implements made by the Inuit in comparison to the simple bone points made by the Tasmanians.

Polar Eskimo

Climatic changes in the area occupied by the Polar Eskimo can be tracked for the past 1250 years with climatic reconstructions based on varved sediments from the Cape Dyer region, Baffin Island [15]. The Cape Dyer region is close to the homeland of the Polar Eskimo and the two regions would have had similar climatic conditions. These data indicate that the Little Ice Age began around 1375 AD in this region and this would be the period when the Polar Eskimo became isolated from other groups. Historical records from early Arctic explorations document the isolation of the Polar Eskimo and provide estimates on their total population size. An Inuit account of a migration from Baffin Island to the Polar Eskimo around 1860 is used to document both the rarity of such migrations and the reintroduction of the kayak, bow and arrow and fish leister to the Polar Eskimo. This provides a natural experiment for testing the extent to which making complex implements can be incorporated by a group with a small, interaction population size and

whether the skills can be passed on to subsequent generations in a small interaction population even absent the skilled persons who were the initial target persons for making these implements.

Angmaksalik Inuit

The Angmaksalik Inuit of eastern Greenland are used as another test case for showing that the Inuit, even with small interaction population sizes, made highly complex implements. The isolation of the Angmaksalik Inuit is measured through their geographical isolation (600 km from the nearest Inuit groups in southern Greenland), their genetic distinctiveness regarding mtDNA haplotypes, and the fact that the population size of Greenland was, until recently, below the interaction population size assumed for the Tasmanians.

Fishing Implements in Oceania

The database used in [4] is reviewed for consistency with the Kline and Boyd's statement that only a group with a subsistence economy should be included. By their criterion, Hawaii should not be included in the database. Hawaii is also a statistical outlier. The data are reanalyzed without Hawaii, using a statistical linear regression model as did the authors. This makes it possible to determine the extent to which their results depend on Hawaii being in their database. A measure of fishing risk based on ocean currents and not considered by the authors is introduced. An estimate of the degree of fishing risk from ocean currents is measured for each of the nine groups in the database of subsistence fishing groups by characterizing an island (or islands) for a group as either protected, partially protected, or not protected from ocean currents. "Protected" is defined as a group living on a ring of islands or an island surrounded by an atoll. "Partially protected" means the group has been living on an island

with substantial bays or inlets that protect against ocean currents or with one side of the island protected against ocean currents by reefs. "Not protected" is defined as an island for which the entire coastline is directly exposed to ocean currents. The topography of the islands was determined from satellite images obtained using Google Earth (see Figure A1 in the Appendix).

Results

Even though the model makes an invalid assumption, it might still be the case that populations with greater interactive population size produce more complex artifacts, keeping fixed the mode of adaptation. Consider first the case of Tasmania. Tasmania is used as an example of the model in action by assuming $\Delta \bar{z} = 0$ until about 8,000 *ya* when rising sea levels isolated Tasmania from mainland Australia and the interaction population size decreased, leading to a reduction in the skill level of the most skilled person being imitated, hence to a decrease in the average skill level of the imitators [1]. This had the consequence, it is claimed, that they no longer had the skills needed to make bone points. Similarly, Kline and Boyd [3] argue that Oceanic Island groups with greater than average rates of contact with other island groups had larger interaction population sizes and so the average skill level of fishing implements in these islands would be greater. The model would account, they claim, for what they assert are more complex fishing implements made by groups with higher rates of contact with other islander groups, controlling for the interaction population size of the group. However, in both cases reanalysis of the data does not support the claims.

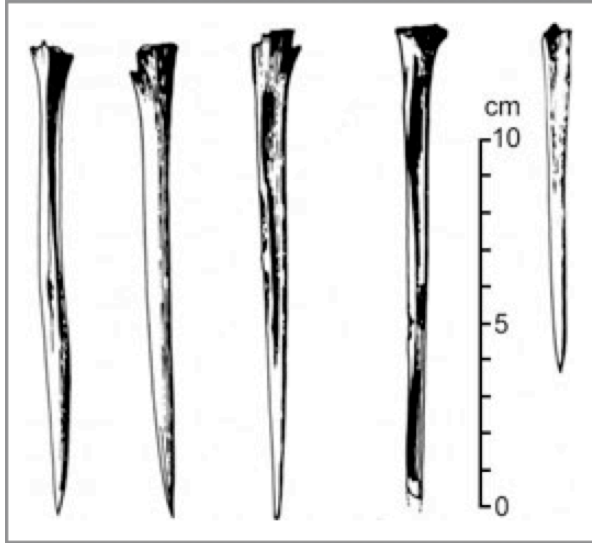


Figure 1: Bone points from Cave Bay Cave, Tasmania. Drawings are as depicted in [12] and adapted from [13].

Results Obtained from Data on the Tasmanians

Before 8,000 *ya*, the Tasmanians used simple bone points (see Figure 1) to make simple clothing to protect themselves against their cold climate [17]. Sites with bone points occur most frequently during the coldest period and they disappeared about 4,000 years after major amelioration of the climate took place (see Figure 2).⁹

Since the only tool loss was the bone points and innovation continued to take place with stone tools, the bone points must have required greater skill to make than the stone tools in order for the model to explain the disappearance of bone points while innovation continued with the stone tools. Henrich recognized the potential problem and referred, without providing any reference or evidence, to “the difficulty of learning how to make ... complex tools such as ... fine bone implements” [p. 204 in 1]. The “fine bone implements” are the bone points shown in Figure 1. “Fine” refers to the point being needle-like in

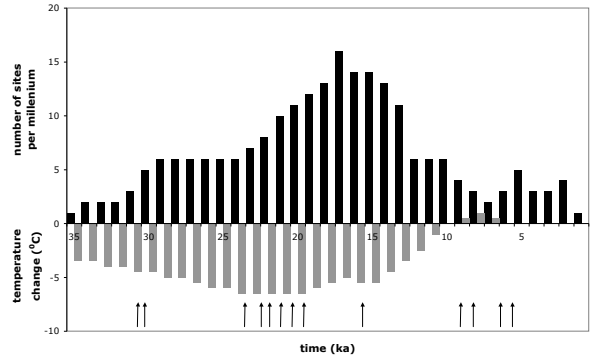


Figure 2: Climate change in Tasmania. Onset of warmer climate occurs around 10,000 *ya* (bottom part of figure). Each arrow corresponds to a site, or a layer in a site, in which bone points have been found. Bone points disappear after the onset of a warmer climate. Bone points from the warmer time period after 10,000 BP are from the Rocky Cape site and may not have been used for making clothing [16]. Analysis of bone point residues from Rocky Cape shows that they might have been used for fish processing [19] and there is a strong linear relation between number of fish bones and number of bone tools ($r = 0.96$) [Figure 7.5 in 18]. [[Accordingly, the primary use of bone points for making clothing stopped with the amelioration of climatic conditions, starting 15,000 *ya*, and the secondary use of bone points with fish processing stopped when fish were no longer obtained after 3500 *ya*.]] (Data on sites with bone points are from [20-22]. Figure reproduced and modified from [23], Figure 2 by permission of *Antiquity*.)

its shape at one end. However, these bone tools “are ... a low-level innovation, are easy to make...” [p. 355 in 25] and points like this can be manufactured by longitudinal scraping with a stone flake [26-28], suggesting that a high degree of skill is not needed for making the Tasmanian bone points. In any case, no data are provided for asserting that the Tas-

manian bone points required greater skill to make than stone tools.

In addition, it must be assumed that the interaction population size included groups on the mainland part of Australia; otherwise, there was no decrease in the interaction population size when Tasmania became isolated. However, the degree of, and geographic spread for, integration of local groups into a population of interacting learners is unknown. Henrich simply assumed it included about as many people from the mainland of Australia as there were in Tasmania. The interaction population size model implies, as pointed out by an anonymous reviewer, that the quality of the bone points should decrease through time as the average skill level decreased, but there is no evidence showing that bone points made after Tasmania was isolated from the mainland are of any less quality than bone points made previous to that event. Finally, the model attempts to explain a nonexistent anomaly. There is nothing anomalous about the simplicity of the collection of tools used by the Tasmanians. Their ensemble of tools is consistent with the well-documented pattern for variation in tool complexity found among hunter-gatherer groups ranging from tropical to temperate to Arctic conditions (see Figure 3). Overall, the simplest explanation for the disappearance of the bone points is that the Tasmanians stopped making them when they no longer needed to make clothing.

Results Obtained from Data on Variation in the Complexity of Hunter-Gatherer Implements

The last observation about the well-documented pattern for variation in the complexity of tools among hunter-gatherer groups needs further elaboration as the pattern is at odds with the assumption that the interaction

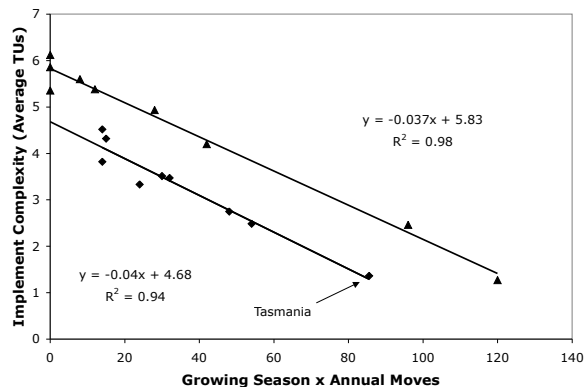


Figure 3: Plot of 18 hunter-gatherer societies, tool complexity versus interaction of risk and number of annual moves. Symbols (from left to right): Triangles—Hunter-gatherers with collector strategy: Angmak-salik Inuit, Inglulik Inuit, Tareumiut Inuit, Tanaina, Ingalik, Twana, Nabesna, Ingura, Tiwi; Diamonds—Hunter-gatherers with forager strategy: Owens Valley Paiute, Copper Inuit, Tlingit, Nharo, Klamath, Caribou Inuit, Chenchu, Surprise Valley Paiute, Tasmania. See [7] for more details. Modified from Figure 5 in [7].

population size is the driver for artifact complexity. Hunter-gathers have made more complex implements as a way to reduce risk in obtaining animal food resources, where risk refers to the chance of failing to detect an animal in a given hunting episode, the likelihood of not killing it once it was detected, and the cost of such a failure [29].

Groups should be willing to invest more time and effort in making and maintaining more complex tools (that is, tools better designed for success in the task at hand) when they are faced with higher risk conditions. This hypothesis was tested by Robin Torrence [30] and found to be supported strongly by evidence from hunter-gatherer groups from a wide range of environmental conditions. Torrence used latitude as a simple proxy measure

for risk since ecological and environmental conditions vary more-or-less monotonically with latitude and increasing degree of risk should relate to increasingly harsher ecological and environmental conditions as one goes from the equator to the Arctic.

Another factor suggested as a determinant of the complexity of implements is the frequency with which a hunter-gatherer group changes its location, under the assumption that time and energy spent in relocation competes with time for that can be used for making, maintaining and transporting more complex implements [31]. Data on the relationship between frequency of relocation and complexity of implements, by itself, show at most a weak relationship. A strong relationship occurs, however, when an interaction effect between degree of risk and frequency of relocation is taken into account (see Figure 3 and discussion in [7]; [[see also Figure 4 in [7] showing a curvilinear relationship between number of complex tools and the interaction effect). The empirical and theoretical reasons for the patterns shown in Figure 3 and in Figure 4 in [7], beginning with the role of risk and mobility in hunter-gatherer food procurement, have been discussed in detail by Robert Kelly [33]. He argues that this pattern is to be expected once we consider how decision-making processes that balance investment cost against reward opportunity apply to choice of technology for making artifacts for food procurement. In brief, based on a technology investment model ([34] - [35]) with investment costs amortized over the expected use life of technological investment made in producing more complex artifacts, investment in more complex technology and artifacts would occur when “the resource acquired with that more costly technology has become more important to the diet...” [page 5.13 in [33]]. Given the strong relationship

shown in Figure 3,]]¹⁰ the model of interaction population size as a driver of implement complexity would require that this pattern be due to the interaction population size co-varying with risk. However, proxy measures for the interaction population size such as the population size of a group or the population density do not co-vary with risk. Mark Collard and coworkers [32] and Read [7] each showed that population size and risk vary independently and Read [35] showed the same is true for population density and risk.

Population density – but excluding island populations for obvious reasons – is a good proxy measure for the interaction population size under virtually any plausible geographical model for variation in the latter variable. For example, if groups interact with other groups up to a fixed distance D that determines the interaction population size, then interaction population size varies linearly with population density. Alternatively, if the distance D for interaction is not constant but varies monotonically with the interaction population size (e.g., D is smaller with higher density than with lower density populations), then the interaction population size will still vary monotonically with density, and so on. Hence the independence of population density with implement complexity shows that interaction population size does not vary in a geographically determined manner.

The only way to accommodate interaction population size within the demonstrated, strong relationship between the risk and annual moves interaction effect and the complexity of implements would be for risk to also be a causal factor for the interaction population size. While this is possible, it contradicts the model’s assumption of interaction population size as the driver for artifact complexity and would require, instead, that the relationship between interaction population

size and tool complexity be one of association and not causation. In addition, it implies an improbable geographic spread for the interaction population size of Arctic groups with complex implements. If $n = 8,000$ Tasmanians is the interaction population size needed to have individuals with sufficient skills for the imitators to be able to make bone points ($TU = 1$), then the interaction population size needed for the Inuit in the Nunavut region of northern Canada to have made tools with an average of 5-6 TUs per tool type (and individual tools with up to 30 TUs) would be much larger. Yet even with $n = 8,000$ persons and using the modern day population density of 0.015 person/ km^2 for the Nunavut region of northern Canada [36] (which overestimates the population density for the region prior to European contact), the persons making up the interaction population size for a single group would be distributed, on average, over $533,000$ km^2 , an area larger than the state of California.

According to the model for complexity to be due to the interaction population size, the latter would more likely be at least on the order of $n = 24,000$ persons in order to make the far more complex implements made by the Inuit, as $n = 24,000$ corresponds to about a 10% increase in the expected skill level of the most skilled individual who would be the target producer for the complex artifacts.¹¹ If $n = 24,000$, the required area would be $\sim 1,600,000$ km^2 , an area larger than the state of Alaska. That 24,000 persons distributed throughout a region the size of Alaska would constitute an interaction population of “well connected” social learners hardly seems plausible. In addition, 24,000 persons is $1/3$ of the total number of the estimated $n = 73,770$ North American Inuit at the time of European contact [37].

Results Obtained from Data on the Polar Eskimo

When we turn to the Polar Eskimo, for whom we have historical evidence for the size of their interaction population, the data are even less persuasive for tool complexity to be caused by the interaction population size. Europeans did not contact the Polar Eskimo of northern Greenland until the Arctic expedition of John Ross in 1818. Ross had an Inuit guide from southern Greenland with him who could communicate with the Polar Eskimo. The Polar Eskimo told Ross that they could not imagine where Ross, his crew and ships had come from, as they did not know of any group of humans other than themselves.¹² The Polar Eskimo apparently had been isolated from the rest of the world from some time during the Little Ice Age that began around 1375 AD in this region and continued for 400 years (see Figure 12 in [15]). They numbered at most about 200 persons when encountered by Ross [41] and since they did not have contact with any other group for several centuries [41], their interaction population size was also 200, an order of magnitude smaller than the 4,000 persons assumed by Henrich not to be large enough to have persons sufficiently skilled to be able to make simple bone points. Yet the Polar Eskimo had a variety of complex tools and implements that they made to survive under the extreme Arctic conditions with which they had to cope. Their tools included a sophisticated sled, multipart harpoons, hafted knives and other complex items. That they had lived in isolation for several centuries indicates that even a small group of 200 has individuals with sufficient skills to make complex implements.

The Polar Eskimo, however, did not have the kayak, bow and arrow, and fish leisters that were common in other Inuit groups. Two

hypotheses have been advanced for the lack of these implements. One stems from an oral account recorded by Knut Rasmussen in 1903-04 [42] and told to him by the descendant of one of a group of Inuit from Baffin Island who, after being informed by Commander Inglefield of the British naval ship Phoenix about the Polar Eskimo, decided to migrate to them. Before being informed by Inglefield, they did not know about the existence of the Polar Eskimo [41]. The migrants arrived around 1862 after a several-year migration. The group of Inuit arriving from Baffin Island lived with the Polar Eskimo for around six years before attempting to return to Baffin Island, a trek during which most of them starved to death. The oral history recorded by Rasmussen from a descendant of one of the few survivors of this group reports that the Polar Eskimo had a legend about a disease wiping out all of the older persons who knew how to make kayaks and so the knowledge needed for kayak making was lost to them.

The other hypothesis sees the loss occurring during the Little Ice Age when they become isolated due to the development of extensive sea ice for long periods of time during the year. This may have made the use of kayaks impractical or of little use. Also, caribou were not a major resource in this part of the Arctic: “Artiodactyls [caribou and musk oxen] are relatively low-ranked prey in [central] Canadian coastal Paleoeskimo sites” [p. 157 in 43]. For the area occupied by the Polar Eskimo, out of 15 early, middle and late Dorset archaeological sites predating the Polar Eskimo, 12 have no caribou remains and 3 almost no remains whereas several have substantial musk ox remains [Tables 4.3, 5.3 in 43]. In no archaeological site in this region is there an abundance of caribou bone remains. Also, it may not have been feasible

for them to have hunted both musk oxen and caribou [40] because of their different habitats [44]. In addition, with the increase in sea ice they were cut off from driftwood and so did not have the wood needed to make kayaks or implements such as a bow and arrow. With lack of wood to make bows, and the marginality of caribou in the diet, it is not surprising that the Polar Eskimo stopped hunting caribou [40].¹³

Under either hypothesis, it should be noted, the loss of the implements is not due to reduction in the size of the interaction population size but to external circumstances. One hypothesis attributes the loss of the implements to the equivalent of genetic drift and the other to changed environmental conditions.

The Polar Eskimo also provide a test case for the effect of the size of the interaction population on imitation/learning when migrants arrive with the skills needed for making complex implements. While living with the Polar Eskimo, the migrants taught them to make kayaks, bows and arrows, and other implements [40, 42]. Perhaps fortuitously, temperatures had ameliorated around the time of this migration and the average temperature had increased by $0.4^{\circ}\text{C} = 0.72^{\circ}\text{F}$ (see Figure 12 in [15]). The temperature increase may have made use of kayaks and hunting of caribou more feasible than it was during the Little Ice Age and wood for making kayaks, bows and arrows and leisters was now available through contact with whalers. Although their population size was around 100 - 200 persons when the migrants arrived, the Polar Eskimo neither had difficulty learning to make these implements nor in continuing to make them after the target persons left their group. This incident demonstrates that even a group of 200 persons has enough individuals with the

skills needed to make complex implements [7].

The fact that the migrating Inuit did not know about the Polar Eskimo until informed by the commander of a British vessel, the difficulties the migrating group had in reaching the Polar Eskimo, and the fact that most of them died on the return migration indicate that migration to or from the Polar Eskimos must have been a rare event – sufficiently rare that the Polar Eskimo believed themselves to be the only humans as recorded by Ross in his records from the 1818 expedition. It was only after establishing contact with West Greenland in 1904 that non-Polar Eskimo began to be added to their population [45].

Results Obtained from Data on the Angmaksalik Inuit

The Polar Eskimo were not the only isolated or nearly isolated group in the Arctic.¹⁴ The Angmaksalik Inuit, on the east coast of Greenland, were isolated from the nearest, other Inuit groups in southern Greenland by 600 km of coastline (as the crow flies) that was difficult to traverse [48]. The total population of East Greenland was about 420 persons in 1883, the earliest date for which Danish census figures are available [Table 2 in 49]. Though there are no records regarding rates of migration between the Angmaksalik Inuit and the Inuit in southern Greenland, their mtDNA haplotype frequencies distinguish them from each other [50], which means that drift was a more important factor than migration in structuring their mtDNA haplotype frequencies: “the current differences indicate that drift has outweighed gene flow” [51]. Genetically, their mtDNA haplotype frequencies most closely resemble those of the Dorset people [50] that occupied the Arctic area before the expansion of the Thule people, the immediate ancestors of the Inuit,

from Alaska after 1200 AD [52].¹⁵ These data underscore the relative isolation of this group, yet they produced the most complex tools of all hunter-gatherer groups (one harpoon had 35 TUs [14]) despite what appears to be a small interaction population size.

Could they, or any of the Inuit groups in Greenland, have had an interaction population size of a size comparable to the Tasmanians with their assumed interaction population size of $n = 8,000$? To do this would have been extremely difficult since only the coast of Greenland was occupied and so one would only find 8,000 persons by first traveling 600 km to the southern part of Greenland and then up the west coast. The population of West Greenland was about 5,120 persons in 1789 [Table 1 in 48]. So in combination with the population of East Greenland, there were, before European contact, fewer than 6,000 persons spread out over more than 2300 km of coastline as the crow flies. The likely interaction population size of at least $n = 24,000$ required by the interaction population model would include, as already noted, about one-third of the estimated total population of 73,000 Inuit in all of North America before European contact and would have involved a substantial portion of the upper Canadian Arctic — an area largely, if not totally, isolated from the Inuit in East Greenland during the Little Ice Age and immediately afterwards. The population of Greenland did not reach 24,000 persons until after 1950 (see Figure 3 in [54]). It is hardly possible, then, to have had a “well connected” population of 8,000, let alone 24,000, Inuit social learners for any of the Inuit in Greenland when the Inuit were living a traditional hunter-gatherer life style, yet all were making complex implements.

Results Obtained from Data on Fishing Implements from Oceania

Kline and Boyd [4] recognized the problem posed for the interaction population size model by the data on population size and/or density and complexity of tools [7, 32-35], but dismissed it because the contact rates with other groups for the groups in the data set are unknown and so we do not know their interaction population size. To address this limitation, they considered Oceanic Island groups, as there is enough data on contact rates with other groups to permit characterizing the inhabitants of a given island as either having a low or high rate of contact with other island populations. Kline and Boyd then used ethnographic data on ten island fishing groups to determine the number of types of fishing related implements each group had, the complexity of the implements (measured as the average number of TUs per implement), the population size for each group, and its contact rate with other groups measured as low or high. They also included a variety of environmental variables in their data set.

They presented four statistical results asserted to support the model of artifact complexity determined by the interaction population size. First, they found that $\log(\text{number of types of implements})$ varies linearly and significantly with $\log(\text{population size})$ ($p = 0.005$). Second, they found that the proportion of high contact groups above, and low contact groups below, the regression line for $\log(\text{number of types})$ regressed on $\log(\text{population size})$ was in the predicted direction and almost significant ($p = 0.075$). Third, the complexity of the fish implements measured by $\log(\text{average number of TUs})$ varied significantly with $\log(\text{population size})$ ($p = 0.02$). Fourth, the model with contact rates included as an independent variable in addition to population size ranked 6th among all

models with population size and a second, independent variable when complexity of implements is the dependent variable.

Of these four results, while the second one is consistent (but not statistically significant) with the hypothesized model, the fourth one contradicts the claim that it is the interaction population size and not the population size that relates to implement complexity. The model for relating interaction population size to tool complexity implies that, of the variables included by them, population size in conjunction with contact rates should be the best predictor of the complexity of tools. They find, instead, that “population size and contact is the sixth most-preferred model for predicting tool complexity...” [p. 2561 in 4] out of all possible models with both population size and one of the other measures as the independent variables. The ranking is based on Akaike’s information theoretic statistic computed for each of the models. The “non-significance” of the measure of contact indicated by the low ranking is also shown by the value of $p = 0.60$ for the regression model when $\log(\text{population size})$ and contact are included as the independent variables.

Their first and third results both use population size as an explanatory variable for tool complexity. However, the first result, relating population size to number of tool types, does not control for the fact that the number of types may vary with population size for reasons unrelated to implement complexity. For example, as noted by Kline and Boyd [4], subgroups within a large population may differentiate among themselves [55] and make different types of implements of the same complexity for the same task, hence creating a positive association between the number of types of implements and interaction population size without change in implement complexity. The third result, as we will now see,

is based on an outlier. One of the ten groups in the data set, Hawaii, did not have an economy based on subsistence fishing as happens with all the other groups in the data set.

Instead of a subsistence economy, Hawaii had a barter economy (there was no monetary system) centered on “managing an ecologically complex integrated farming system that connected agricultural watersheds to oceanic environments,” a complex comparable “to integrated farming systems developed in ancient China and Egypt” [p. 328 in 56]. Their barter economy made extensive use of fish farming [56] and produced a surplus used in trade and exchange. Before 1900, the output of the fish farms was substantial and estimated to be at least 900,000 kg per year [Table 1 in 56]. The farming complex, with its integrated fish farms, sustained a large population size and density [56] and was a unique system in the Pacific Islands [57-58].

The difference in economies between Hawaii and the other island groups in the data set runs contrary to Kline and Boyd’s observation that Henrich’s [1] model of cultural adaptation “predicts that *in the same economic and ecological circumstances*, smaller, isolated populations will have simpler tool kits” [p. 2559 in 4, emphasis added], where “By ‘economic’ we mean in the sense that it is not a market economy, and that *it is subsistence living...*” [59, emphasis added]. In other words, they argue that all the island groups included in the data set should have subsistence economies.

Henrich [p. 779 in 2] notes the need to control for environmental and ecological differences. Though he does not mention economic differences, his comments about the need to control for environmental and ecological differences are in line with Kline and Boyd’s observation that “ecological and economic factors may affect the kinds of tools

that people use” [p. 2559 in 4]. Variation in economic and/or ecological circumstances can affect tool complexity and if it is due to differences in the interaction population size, then differences in economy and/or ecology will be confounding factors when considering the effect that variation in interaction population size has on tool complexity. Kline and Boyd controlled for these other factors by limiting their analysis to groups with the same economy and ecology, namely Oceanic Island groups with a subsistence economy.

Restriction of groups in the data set in this way assures commonality in having groups where resource production is aimed at satisfying local consumption and not at producing a surplus to be used in exchange and trade, as happens in market economies. In economies aimed at producing surpluses, complexity of implements may relate, in part, to efficiency of production. Consequently, if the interaction population size is larger with a market versus a subsistence economy, then a statistically positive relationship between interaction population size and complexity of tools could be due to differences in economic factors rather than the demographic process modeled by Henrich [1] should both kinds of economy be included in the data set. Hence the need to control for differences in economies.

The differences in population size, density and economy between traditional Hawaii and the other island groups in the data set also have the consequence of making Hawaii a statistical outlier in comparison to the statistical pattern found with the other groups in the data set. As can be seen in Figures 4 - 6, there is a linear relationship between population size and number of tool types and the data point for Hawaii is an outlier for this linear relationship.¹⁶ Consequently, we need to remove Hawaii from the data set to determine if the pattern found when Hawaii is included

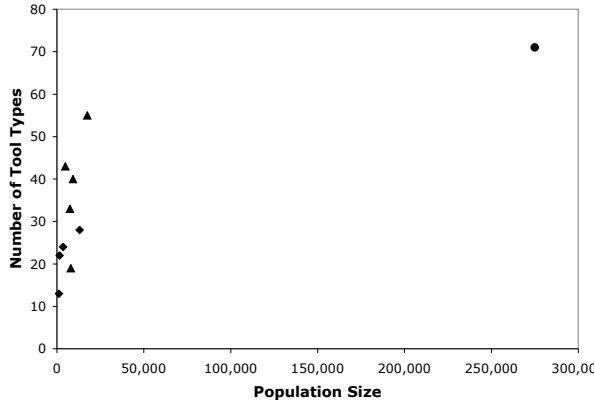


Figure 4: Plot of number of tool types versus population size. Triangles: islands that had high contact rates with other islands. Diamonds: islands that had low contact rates with other islands. Solid circle: Hawaii. Relationship between tool types and population size is linear except for Hawaii, which is an outlier. Data in this and Figures 5-6 are from [4].

in the data set is still present after Hawaii is removed. If Hawaii is not an outlier, then the same patterning, though attenuated, should still be found.

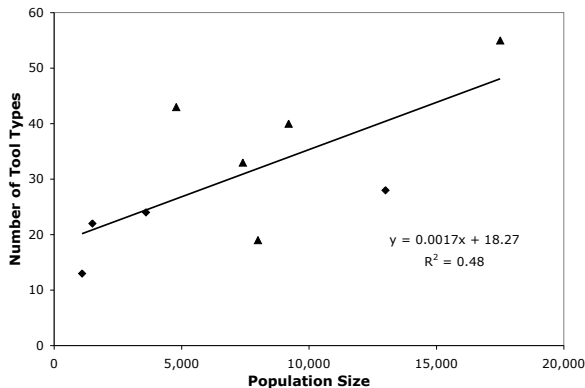


Figure 5: Plot of number of tool types versus population size with Hawaii removed. Triangles: islands that had low contact with other island groups. Diamonds: islands that had high contact with other island groups. The linear regression line is significant at the 5% level ($p = 0.04$).

With Hawaii excluded, the statistical results no longer support their argument. First, the distribution of high contact and low contact cases around the linear regression line for number of tool types (see Figure 5) is not significant ($p = 0.17$, Fisher Exact Test, one-tailed). Second, the linear regression between population size and tool complexity is not significant ($p = 0.08$, without log transformation) (see Figure 6). Third, the distribution of high contact and low contact cases around the regression line for tool complexity is not significant ($p = 0.64$, Fisher Exact Test, one-tailed) (see Figure 6). The single pattern that is only attenuated by the removal of Hawaii is the linear regression between population size

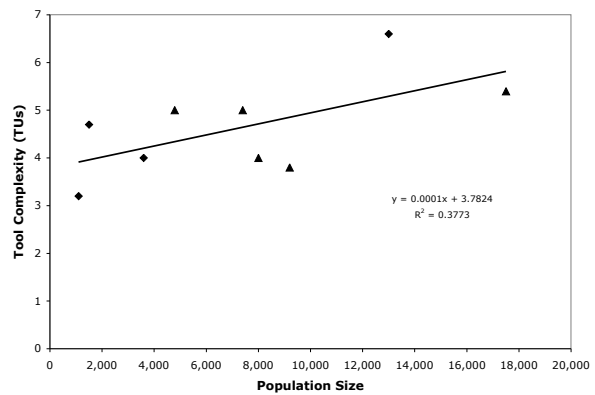


Figure 6: Plot of tool complexity versus population size with Hawaii removed. Triangles: islands that had low contact with other island groups. Diamonds: islands that had high contact with other island groups. The linear regression line is not significant ($p = 0.08$).

and number of tool types, which is now significant only at the 5% level ($p = 0.04$, without log transformation). However, this relationship may be due to increased differentiation in subgroups in larger populations as discussed above. In any case, this relationship between population size and number of tool types is secondary to the relationship of pri-

mary interest, namely the relationship between the interaction population size and tool complexity, which is not supported without Hawaii in the data set.

In contrast with their analysis, there is a well supported model for variation in artifact complexity among hunter-gatherer groups, namely the risk model [7, 30, 32-35]. In that model, risk is measured by the length of growing season as a proxy variable [7]. For all the Oceania Islands, however, there is a growing season of 12 months and so length of growing season does not measure risk differences among the island groups. Risk, the likelihood of failing to obtain fish on a given fishing episode, whether fishing by line and hook, nets, or traps, relates to ocean currents [60-61] and the relative importance of ocean currents as a risk factor depends on the degree to which a group has areas for fishing that are protected from ocean currents and the strength of the ocean currents.

To measure this source of risk, each island (or group of islands) was characterized as protected, partially protected, or not protected based on its topography. Table 1 shows the groups, the complexity measure for fishing implements, the population size and the degree of protection for each group. Of the three measures of concern – population size, degree of contact, and degree of protection – only the last one has a significant correlation with the complexity of fishing implements ($r = 0.71$, $p = 0.03$; yes = 1, partially = 2, no = 3). Thus it appears that variation in fishing tool complexity in Oceania may be due to variation in risk, a pattern consistent with data from hunter-gather societies [7, 30, 64-65].

Oceania Data and Model Selection

Another way Kline and Boyd attempt to support their claim about the relationship be-

group	mean TU	popula- tion	contact	geography	protected?
Malekula	3.2	1 100	low	ring	yes
Chuuk	3.8	9 200	high	semi-ring	yes
Santa Cruz	4.0	3 600	low	bays	partially
Trobriand	4.0	8 000	high	bays	partially
Tikopia	4.7	1 500	low	volcanic lake	yes
Yap	5.0	4 791	high	bays	partially*
Lau Fiji	5.0	7 400	high	single is-land	no
Tonga	5.4	17 500	high	several islands	partially**
Manus	6.6	13 000	low	single is-land	no

TU = Technical Units
 Data on TUs, population and contact from [4]
 **"difficulty of fishing Yap's outer reef slope because of the fresh prevailing winds and *strong nearshore currents*" [33, p. 6, emphasis added]
 ***"There are three main groups of islands namely Tongatapu, Ha'apai and Vava'u. The islands are scattered and *separated by strong currents and unpredictable weather patterns.*" [37, p. 7, emphasis added]

tween interaction population size and tool complexity is through ranking all possible models with $\log(\text{population size})$ and one other variable as the independent variables under the presumption that a model based on variables measuring the hypothesized relationship between interaction population size and tool complexity should be more highly ranked than other models if that model is the correct one. For this purpose, they consider two rankings: one with the number of types as the dependent variable in the statistical models and the other with the average TU per implement as the dependent variable. The rankings were made using the Akaike information theoretic statistic computed for each model.

However, their data set does not match the requirement for model selection that all the proposed models have prior justification. Selecting a model using rankings based on the Akaike information theoretic assumes "a set of a priori candidate models has been defined and is *well supported by the underlying science*, then AIC is computed for each of the

approximating models ... Using AIC, the models are then easily ranked from best to worst based on the empirical data at hand” [p. 269 in 66, emphasis added]. For the Oceanic Island data set, even with Hawaii included, in no case is a second variable ever included with population size in the regression model at a statistically significant level. In effect, they are ranking a suite of models, none of which fits the data, to see which of the non-fitting models is the best fitting.

Yet even if we ignore this difficulty, there is the further problem that all the ranked models are equally valid (or equally non-valid). When the difference in the AICc value between the model in question and the model with the smallest AICc value is less than 2, the model in question fits the data as well (or equally badly) as the model with the smallest AICc value [66]. The models tested by Kline and Boyd have AICc values ranging from -3.39 to -3.00 for number of tool types as the dependent variable and from -4.33 to -4.19 for the average number of TUs as the dependent variable. All differences in AICc values between models in either set of models are < 0.4 and so all the models are equally valid (or equally invalid) for these data. The model with independent variables, population size and number of publications, is as valid, according to the AICc values, for predicting the average number of TUs as the model with population size and rate of contact. Yet population size and number of publications is not a valid model for predicting the average number of TUs. In other words, none of the models is valid and so all are equally non-valid.

The same conclusion is obtained from their use of the AICc weights for each of the models. A weight can be interpreted as the probability that the corresponding model is the best information theoretic model for the data in the collection of models being consid-

ered [66]. The virtually identical weights for all the models indicate that all are equally probable as being the best model for the data (or equally probable as being the worst model). No one of the models stands out as being a better model for these data. Since some of the models are obviously not valid, it follows that none of the models is valid.

In sum, the AICc statistics simply reinforce the conclusion from the linear regression analysis that none of the models with a second independent variable selected from the list of variables used by Kline and Boyd is valid for these data. In particular, the model that includes the rate of contact is no more valid than any of the other models they considered, hence these data do not support Kline and Boyd’s claim that rate of contact is relevant to the complexity of the fishing implements. Their claim, however, is critical to the conclusions they draw from their analyses.

Kline and Boyd consider three alternative hypotheses for factors that may account for a relationship between population size and tool kit complexity: (1) tool kit complexity increases the local carrying capacity, (2) large populations are more differentiated and hence have a more diverse tool kit and (3) increase in population size may lead to a broader diet with resources having a lower rate of return and so artifacts are designed to be more efficient. They reject all three hypotheses for the same reason in each case, namely that the hypothesis does not account for the purported relationship between rate of contact and interaction population size. They claim that the first hypothesis does not make it clear “why rates of contact would be linked to larger populations sizes,” the second hypothesis does not “explain the relationship between tool kit complexity and rates of contact” and the third does not “explain the importance of contact” [p. 2563, 2564 in 4]. Yet there is no

statistically significant relationship between rate of contact and population size when controlling for economic and ecological differences, hence none of the alternative hypotheses has been discounted.

Discussion

The model for relating interaction population size to complexity of artifacts implies that the interaction population size causes an increase in complexity of artifacts. The increased complexity arises only because of an invalid, implicit assumption that the difference, α , between the average achieved skill level of the imitators and the skill level of the artifacts made by the target person is constant and does not vary with change in the skill level for the imitated artifacts when there is change in the skill level of the target person. More plausibly, and consistent with Henrich's statement about the magnitude of α varying with the skill level of the target objects, the value of α changes by the same amount as the change in the skill level of the target person.

Empirically, the data from Tasmania and the Oceanic Islands that purportedly demonstrate the model in action do not agree with it. The simplest explanation for why the Tasmanians stopped making the bone tools they had been using to make clothing during extremely cold periods is that the climate ameliorated substantially, they no longer needed to make clothing, and so they stopped making bone points. Variation in the complexity of implements used by Oceanic Island fishing groups that had subsistence economies does not vary with degree of contact with other island groups and appears to vary with risk. In addition, data on hunter-gatherer groups, in general, show that complexity of artifacts neither varies systematically with population size nor population density as proxy measures of the interaction population size, but varies instead

with an interaction effect between risk and frequency of moving to new hunting localities. Further, data on the Polar Eskimo, a group isolated during the Little Ice Age, show that they continued to make complex implements despite a small interaction population size of 150 - 200 persons at time of contact. In addition, they both learned to make kayaks, bows and arrows and fish leisters from a group of migrant Inuit and continued to make these implements after the migrants left. They neither needed a large interaction population to learn again how to make these implements nor to transmit the knowledge and skills across generations. Similarly, the Angmaksalik Inuit, though not as isolated as the Polar Eskimo, were sufficiently isolated so that their mtDNA haplotype frequencies remained distinct from the Inuit groups nearest to them, 600 km to the south, yet they made the most complex tools that have been recorded for hunter-gatherer groups [14]. These results, however, are not specific to just these two Inuit groups.

All the Inuit groups made highly complex implements and in all cases neither population size nor population density, as proxy measures of the interaction population size, varies with tool complexity [7]. [[Nor do Inuit groups with complex tools have a large interaction population size even when the latter is formed by simply summing over all groups in a geographically large region. The Inuit whale hunters of north Alaska, for example, were distributed in three settlement systems separated from each other by hundreds of miles of coastline. Altogether, they totaled only about 1,850 persons when first contacted in the mid 1800's [67].¹⁷ Even if the Inuit groups interior to them from a region of over 360,000 km² are also included in the interaction population, there were still at most 3,000 - 4,000 persons [67], an interaction

population size comparable to that of the Tasmanians. Yet the Tasmanian interaction population size of 4,000 was supposedly too small for them to continue making simple bone points, let alone complex artifacts comparable to those of the Inuit whale hunters.]]

While there has been communication throughout the Arctic as shown by the distribution of art and artifact styles during Dorset times, relative isolation of local groups in the high Arctic has a deep history as shown by archaeological data: “early prehistory of the Arctic might be more usefully considered in terms of a ‘mosaic’ of local populations, each adapted to local resources and local environments over varying periods of time” [p. 272 in 68, as quoted on p. 158 in 39]. Finally, an interaction population size of 24,000 – which would be needed for the expected skill level of the most skilled person to be just 10% greater than the skill level required, according to Henrich, to make the simple bone points in Tasmania – could not have existed in a region such as Greenland before 1950 as the population size of Greenland only reached 24,000 persons after that date.

Yet the idea that the interaction population size could account for increased complexity of artifacts strikes a strongly positive note for many readers – lay and academic – as indicated by the quantity and diversity of articles and books that have referred to this model and to Tasmania as a purported example of the model in action. *Science*, for example, gave prominent coverage to the simulation extension of the interaction population size model by Powell and coworkers in the issue in which their article was published.

The idea that we can simplify the domain of making artifacts with varying degrees of complexity by referring to growth in the interaction population size alone has been an appealing one. Part of the appeal may be that

we know, empirically, that complexity of artifacts may accompany population size. With equally inventive persons, the number of inventions per generation would be proportional to the population size¹⁸ and to the extent that the complexity of artifacts depends on the number of inventions, we would expect larger populations to produce more complex artifacts and to produce them more frequently, assuming it is in the interest of the individuals concerned to do so -- stasis is always a possibility. As complex as the tools of the Inuit may be, they are simple in comparison to the implements made by agricultural societies that operate on a much larger population scale and are dwarfed by the complexity of the machines developed as part of the industrial revolution in large scale societies and now by the devices invented as part of the global information revolution. Similarly, the time scale for the increase in the complexity of artifacts is more rapid in large than small populations, all other things being equal. That complexity of artifacts is both part of the adaptations developed by larger scale societies and part of the reason they are able to be larger scale societies is evident. Conversely, that technologies can and have been lost or forgotten is also without question. With the development of metallurgy, the skills that were part of the production of stone tools lost their relevance, hence these skills were no longer passed on to subsequent generations. Until archaeologists took an interest in reinventing flint knapping skills, the technology of stone tool making – once a technology that our ancestors could not live without – had been lost completely to those living in modern societies. Without question, there have been repeated instances like this in human history in which future generations were not interested in developing or maintaining the knowledge and skills that were part of em-

ploying a particular technology used by the current generation.

Chance loss of knowledge and skills, the equivalent of genetic drift, also plays a role and like genetic drift, is more likely to have had a substantial effect in smaller rather than larger populations. According to their oral history, the Polar Eskimo lost the knowledge for making kayaks through the chance event of a disease that killed off all of those who knew how to make them. Whether their oral history about this event is factually correct is not critical here; undoubtedly, drift effects like this have occurred repeatedly during human history. Yet none of this is what the claim about the relationship of the interaction population size artifact complexity is about. The latter is a claim that size of a population directly affects the skill level that can be achieved due to the statistical fact that larger populations will likely have a few, more highly skilled individuals than can be found in smaller populations along with the (invalid) assumption that the difference between the target skill level and the achieved skill level remains fixed as the population size increases and the expected skill level of the targeted, most skilled person increases.

With the assumption of a fixed difference between what is targeted and what is achieved, a feedback loop then drives the average skills upward simply because of increase in the interaction population size. This, however, is the equivalent of perpetual motion – getting something out without putting anything in – and does not work for the same reason. Achieving higher skill levels in the actual output from the production of artifacts takes work – the time and labor needed to learn to become a skilled potter or arrowhead maker.¹⁹ Students today take courses in calculus and many become proficient in applying the ideas of calculus, thereby achiev-

ing a level of skill in what they can produce that would have been unimaginable 400 or 500 years ago before the ideas of calculus were developed in Europe. This increase in the achieved skill level of students does not derive from an increase in the interaction population size, but is due to the work of making the ideas of calculus more accessible through teaching and of taking complex ideas and breaking them down into easier to comprehend parts that can be learned sequentially. It is the work invested in the process of developing skills that leads to increase in the performance level of what the members of a group or a community can achieve, not the increase in interaction population size.

The florescence of stone tool technology in the European Upper Paleolithic occurred not as a consequence of the interaction population size increasing, but because a variety of ideas, some relating to technology and others, critically, to new ideas about social relations, were being worked out [71-72]. There was increase in the interaction population size, but it resulted from the basis for the coherency of social units changing from face-to-face interaction to relations conceptualized among the members of a group and so social units no longer had to depend upon prior face-to-face interaction for their coherency [73-74]. This led to an order of magnitude increase in the interaction population size [74]. That this larger interaction population size played a role in the resulting florescence of stone tool technology is undoubtedly the case, but not through the feedback loop hypothesized by Henrich and elaborated on by Powell and coworkers.

Powell and coworkers used genetic data to infer a purported increase in population size during the Middle Stone Age as a way to account for the innovations [75 and references therein] found in the Still Bay (72-70

kya) and Howiesons Poort (65-60 kya) [76] assemblages in South Africa. Yet, the subsequent disappearance of these innovations is not associated with a population decline, though it could be countered that current archaeological evidence may be inadequate for documenting changes in population size during the Middle Stone Age [75]. Moving forward in time from the Middle Stone Age to the Holocene, we find that “the rich and relatively well-known Holocene archaeological record of southern Africa” – contrary to the interaction population size hypothesis – “does not provide a good correlation between evidence for larger, denser populations and more complex tool-kits” [p. 8 in 75]. Instead, the change from Wilton to post-Wilton assemblages in the Late Stone Age shows simplification of technology while, at the same time, the population size increased [75].

As discussed in [75], the Wilton assemblages appear to be associated with a shift to interaction among distant groups [77-78], a change that may have led to an increase in the population size through integration of resources over a wider and more heterogeneous region by the process discussed in [79] rather than through intensification based on more complex and specialized tools. This is consistent with the idea that changes in complexity, in either direction, relate to the way our ancestors (and modern hunter-gatherers) worked out both expanded and differently organized means of adaptation [64, 80] by taking advantage of new modes of social relations and forms of social organization that also facilitated investing the time and energy needed for individually formulated technological inventions to become society-wide innovations. Those inventions, and the complexity of the resulting cultural artifacts, reflect and depend upon the creativity of human agents in a way that is still not well under-

stood [81]. As culture bearers, we interact in a constructed, cultural framework of shared concepts and idea systems that provide commonly understood meaning for our actions and the framework within which creativity takes place. It is creativity that leads to, and implements, complexity.

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Appendix

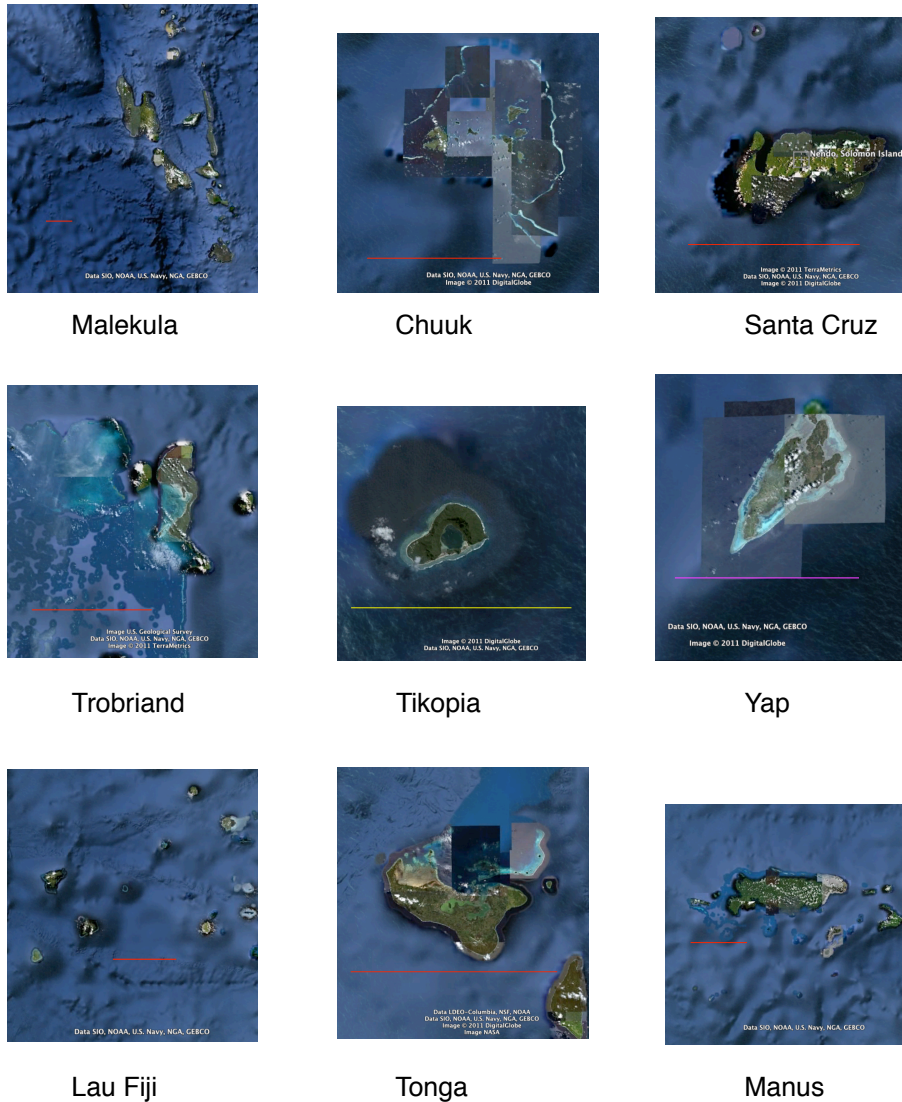


Figure A1: Satellite images of islands corresponding to the fishing implement data. All images are screen captures from Google Earth. The red lines correspond to a distance of 50 km; the magenta line corresponds to a distance of 30 km and the yellow line corresponds to a distance of 5 km. Malekula is one island in a ring of islands forming a protected central area. Chuuk consists of several small islands protected by an atoll surrounding the islands. The main island of Santa Cruz has a large bay and inlets protected from ocean currents. The Tobriand Island is protected from ocean currents only on its southwest side. Tikopia is not protected from ocean currents, but has a large, protected lake in its interior from its volcanic past. Yap has limited protection around its periphery. Lau Fiji consists of several, unprotected islands. Tonga is protected from ocean currents only on its north side. Manus is a large island without protection from ocean currents.

Notes

¹ A review of this article by Joseph Henrich with responses by Dwight Read is available under Supporting Materials.

² Joseph Henrich [2] refers to the size of the population of interacting social learners as “the effective population size,” but this invites confusion with the well-established definition in genetics of the effective population size as the size, N_e , of a panmictic population with the same dispersion of allele frequencies as occurs in the population of size N under consideration. The expression, “interaction population size,” will be used here instead.

³ Henrich does not explain why he used a Gumbel distribution for individual skills. A Google search was unable to locate any researcher who reports a Gumbel distribution for individual skills. However, whether individual skills are distributed normally or with a Gumbel distribution is not critical for the argument being made here. It is critical, though, for the consequences that changes in the size of the interaction population size has on skill levels in the interaction population size model [9]. With a normal distribution of skills, the expected skill level of the most skilled person in an interaction population of size n varies with $(\log n)^{1/2}$, rather than with $\log n$. Consequently, even “going from a population of 5,000 to one of 2,000” has minor effect on average skill levels “when skills are distributed normally” [p. 4 in 9] in the interaction population size model.

⁴ Because of the assumption of a fixed distribution for skills regardless of the magnitude of \bar{z} and since $\Delta\bar{z} > 0$ for large N , the model implies that \bar{z} will increase with each generation of imitators and become indefinitely large as the number of generations increases even for fixed N . More realistically, the distribution of skills becomes increasingly skewed to the left as \bar{z} increases due to inherent limitations on the maximum possible skill levels of individuals and $\Delta\bar{z}$ decreases asymptotically to 0 with increasing \bar{z} .

⁵ The most skilled person needs to be producing an artifact requiring her/his skill level for its production, for if whoever is the currently most skilled person always produces the same kind of artifact, say a simple artifact that can easily be imitated by naive imitators, then introducing an inherently more skilled person through increase in the population size, N , would not change the skill level required for imitating the target artifact. The skill level after imitation would be the same when imitating this simple artifact -- now produced by the newly introduced, more skilled person -- as it was before he or she was introduced as a member of the population. It is the skills required to make the artifact, not the inherent skills of the producer, that is being replicated through imitation and so the target artifact being produced by the most skilled person and then imitated by the population of imitators needs to require the full skill level of the artifact’s producer for its production. Artifact, as the term is used here, includes conceptual entities such as bodies of knowledge in text or oral form.

⁶ It is virtually self-evident that knowledge accumulation and integration leads to future generations being able to do tasks that would have been viewed as accessible only to highly skilled individuals by the members of a past generation. Accumulation of mathematical knowledge over the past several millennia illustrates this accumulation process very clearly [see Figure 2A in 10]. Henrich's claim is of a different sort, namely that the increase in the interaction population size leads to an increase in the expected skill level of the most skilled individual, hence to targets requiring greater skill for their production and thereby, under the assumption of constant α , to an increase in the average skill level in the population. Missing in Henrich's argument is the way in which initially complex tasks can be broken down into a sequential learning process, no step of which requires a major change in skill level from the average skill level associated with the current step in the learning process. Cumulatively, the steps lead to a major increase in the average skill level at which individuals perform. The process of breaking what was initially a complex task into a sequence of learning steps also makes it possible for less skilled individuals to provide the target for the learning process at each step. Thus while only highly educated and skilled individuals probably worked with fractions in ancient Egypt in the manner illustrated in the Rhind Papyrus [11], today children are taught to learn fractions by teachers with only moderate skill levels and who provide the "imitation targets" for the children in a classroom setting. The process of breaking a complex task down into a sequence of learning steps does not depend on an increase in the interacting population size, hence the lack of correlation between the complexity of tools in hunter-gatherer groups and population size [7]. Though the initial production of a complex object or artifact may require a highly skilled individual, at least 5 individuals above the 99th percentile are expected in a hunter-gatherer society of 500 persons. Having a highly skilled individual does not require a large population size.

⁷ An anonymous reviewer commented that Henrich appears to conflate the efficacy with which a task is done and the technique used to do the task, making it unclear what is being modeled. The reviewer gave the example of using heat to dry bone before grinding it to the desired shape. Is this a change in skill level? If the object being made is the reference, then there has been increase in production efficacy but not in the skill level represented by the object. If the reference is the technique of bone preparation before grinding, then there has been an increase in the technique skill level when going from grinding untreated, wet bone to heat treated, dry bone.

⁸ In [35] Dwight Read shows that the Tasmanian tool kit is not unusually simple when relating tool kit complexity to risk measured with the proxy variable, effective temperature, once the unusually low effective temperature for Tasmania in comparison to the length of the growing season is taken into account. As Read shows in [7], the effective temperature of Tasmania (and only Tasmania among the hunter-gatherer groups included in the analysis) is a statistical outlier for the strong linear relationship ($r = 0.97$) between effective temperature and length of growing season. For this and other reasons detailed in [7], the length of the growing season is a better proxy measure for risk and effective temperature drops out when a variable selection procedure is used to determine model variables from a variable set that includes both effective temperature and the length of the growing season. In [7] it is demonstrated that an interaction effect between risk (measured by the length of the growing season) and number of annual moves accounts for 97% of the variation in tool complexity for the 18 hunter-gather groups included in the regression analysis. All of these hunter-gatherer groups, including Tasmania, are consistent with the interaction model for risk and number of annual moves derived in [7].

⁹ Though not directly relevant to the interaction population size hypothesis, the Tasmanians supposedly stopped eating fish after 3500 *ya*. However, the evidence that they ever ate fish is questionable and the single site (Rocky Cape South Cave) where fish bones have been found in quantity are likely from the stomachs of seals hunted by the Tasmanians [24]. In addition, the Tasmanian diet was protein rich and carbohydrate poor. The fish available in the waters of Tasmania are not a source of carbohydrates, but the shellfish consumed in large quantities by the Tasmanians are [7].

¹⁰The text enclosed by double square brackets (here and two instances below) was added while the manuscript was still under review but after it had been sent to the 3rd reviewer. This text was not seen by the 3rd reviewer.

¹¹ Since the expected skill level of the most skilled individual is proportional to $\log N$ in Henrich's model, the change in skill level will be from skill proportional to $\log 8000 = 9.0$ to skill proportional to $\log 24000 = 10.1$, or about a 10% increase.

¹² James VanStone [38] has suggested that the Polar Eskimo were not entirely isolated due to a reference to "southern tribes" in Elisha Kane's report on his 1854 Arctic expedition. VanStone misinterprets this as a reference to Inuit on the west coast of Greenland whereas the reference was to another group of Polar Eskimo [39].

¹³ The Tasmanians and the Polar Eskimo are reported to have had extreme aversion to fish and caribou meat, respectively. That there would be an aversion in two groups for what otherwise is a main food source for other groups in nearby regions is peculiar. One possibility is that in both cases the group had to choose between a nutritionally beneficial and a non-beneficial resource (in the case of the Tasmanians, shellfish provided needed carbohydrates but the fish did not; in the case of the Polar Eskimo, they could only hunt musk oxen or caribou but not both and they lacked the wood needed to make bows and arrows to hunt caribou effectively) and so the culturally prescribed aversion rationalized to them why they did not exploit an otherwise edible, but non-beneficial resource under their circumstances.

¹⁴ In general, Arctic hunter-gather groups were not totally isolated from each other, despite harsh conditions. The Canadian Arctic routes used today when traveling from one area to another with snowmobiles have been identified from oral accounts. It is likely that some of these routes have considerable antiquity [46]. Going back further in time, the Dorset peoples that occupied the Arctic before being replaced by the ancestors of present-day Inuit had extensive systems of communication over time among local groups as evidenced by the similarity in the style of Dorset artifacts throughout the Arctic. Nonetheless, despite possibly having an interaction population more extensive than a local group as is suggested by the similarity in artifact styles, the Dorset peoples abandoned the use of bows and arrows, knew about but did not make use of kayaks, did not make complex harpoons as did the Inuit who replaced them, and had dogs but did not use dog sleds for transportation over snow and ice [47]. The abandonment of these artifacts may have related to changes in their resource base due to worsening climatic conditions. The Polar Eskimo may have done likewise and for the same reason with the arrival of the Little Ice Age.

¹⁵ The East Greenland Inuit do not appear to have ancestry going back to the Paleo-Eskimo dispersal into the eastern Arctic and Greenland around 4500 BP [53], suggesting that their ancestry only traces back to the later Dorset expansion. The genetic relationship between the Paleo-Eskimo and the Dorset is currently unclear, though, as the mtDNA data for the Dorset has only been sequenced to the haplotype group D level and not to the sub-groupings of group D needed to determine the genetic relationship of the Dorset cultures to the Paleo-Eskimo or the neo-Eskimo ancestors of the Inuit [53].

¹⁶ The linear relationship, it should be noted, contradicts the expected “concave relationship between population size and technological complexity” [4, p. 2560] implied by the model relating the interaction population size to tool complexity.

¹⁷ Incorporating all Inuit settlements in a large geographic region into the interaction population ignores social relations among settlements that ranged from cooperative to hostile; e.g., when one group had no ties to another group they were strangers to each other and “A stranger could be killed at sight ...” [p. 333 in 67]. More realistically, the Inuit of this region were a patchwork of interacting groups, not the integrated interaction population described by Henrich [1], hence the population figures for the region as a whole overestimate the size of the interaction population for a single group within this region.

¹⁸ The number of contributions in various academic disciplines has increased exponentially with time [69, discussed in 70], as has the population size over the same time period, but at approximately twice the rate, implying that there has also been an interaction effect among individuals for the number of contributions [70].

¹⁹ Alex Mesoudi [10] argues, for essentially this reason, that the interacting population size model, $\Delta \bar{z} = -\alpha + \beta(\varepsilon + \log N)$, needs to include a term expressing the cost of imitation (otherwise \bar{z} would increase indefinitely) and includes an imitation cost proportional to the current value of \bar{z} by modifying the model so that it becomes $\Delta \bar{z} = -\alpha \bar{z}_0 + \beta(\varepsilon + \log N)$, where \bar{z}_0 is the average skill level before imitation. With this modification, \bar{z} asymptotically reaches a maximum value through time [Figures 3 - 4 in 10]. The same effect of bounding \bar{z} from above occurs when the model is made more realistic through increasing the left skewness of the skill distribution among the imitators as \bar{z} increases (see Footnote 3). Though motivated by different arguments, the models considered by Henrich [1], Mesoudi [10] and Read (above) are formally the same: $\Delta \bar{z} = -\alpha^* + \beta(\varepsilon + \log N)$, where α^* stands for the functional form of the imitation bias assumed in each of the models. Henrich assumes $\alpha^* = \alpha$, a constant inherent to the process of imitation, hence α (and so α^*) is independent of z_h , the skill level of the most skilled, target person in the population. Mesoudi also assumes α is independent of z_h , but then makes the additional assumption that $\alpha^* = \alpha \bar{z}_0$ and so the imitation bias, α^* , is not constant but varies in proportion to the current average skill level. Read assumes $\alpha^* = \alpha_h + (z_k - z_h)$ when the imitators are imitating a target z_k requiring skill level greater than the maximal skill level of the imitators, where α_h is the imitation bias that occurs when imitating a person with skill level z_h at least as great as the maximum skill level of the imitators (i.e., when the imitators are already doing their best, they do not do better by imitating a target that requires an even higher skill level). Mesoudi's model for the imitation bias has the same effect as Read's (namely the imitation bias increases with \bar{z} until $\Delta \bar{z} = 0$) but differs by Mesoudi assuming that the maximum skill level of the imitators is determined through factors external to the imitators via the cost of imitation, whereas Read assumes the maximum skill level is inherent to the imitators. Both external cost and inherent limits are relevant and could be incorporated in a single model.