Weapons of Mass Destruction? Rapa Nui *Mata’a* Morphometric Analyses

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Rapa Nui (Easter Island, Chile) is a tiny island located in a remote corner of Eastern Polynesia, more than 2000 km from the nearest inhabited body of land (Figure 1). Polynesians first colonized the island when they sailed from central East Polynesia in voyaging canoes during the 13th century AD (Hunt & Lipo 2006; Wilmshurst et al. 2011). Despite the island's diminutive size, remoteness, and limited natural resources, the archaeological record of Rapa Nui is well-known for its nearly 1000 multi-ton statues known as *moai* that once sat atop massive stone platforms (Hunt & Lipo 2011a). The magnitude of cultural elaboration stands in marked contrast to the island’s desolate environment and low population levels. While earlier researchers (e.g., Heyerdahl & Ferdon 1961a; Heyerdahl 1989) believed the state of the island was the result of conflict between Polynesians and South Americans, more recent researchers argue that the contrast between the *moai* and the islands landscape is the outcome of an environmental catastrophe (Bahn & Flenley 1992; Flenley & Bahn 2003). This account has been popularized as the "collapse" scenario (*sensu* Diamond 1995, 2005).

New research challenges this notion with empirical evidence that demonstrates Rapanui people flourished on the island until AD 1722 when Europeans arrived (Hunt 2007; Hunt & Lipo 2007; Hunt & Lipo 2009a; Hunt & Lipo 2009b; Hunt & Lipo 2011a; Hunt & Lipo 2011b; Lipo & Hunt 2009; Mulrooney et al. 2009; Mulrooney 2012; Rainbird 2002). Contrary to assumptions about large past population sizes, Rapa Nui's settlement patterns demonstrate that the inhabitants lived in a dispersed and low-density fashion (Hunt & Lipo 2011a; Morrison 2012). We also have learned that prehistoric people lithic mulch to boost island’s nutrient-poor soil to a level that sustained sweet potato cultivation (Bork et al. 2004; Ladefoged et al. 2005; Ladefoged et al. 2010; Ladefoged et al. 2013; Mieth et al. 2006; Stevenson & Haoa 2002; Stevenson et al. 2006). Finally, we now know that the loss of the palm tree forest had nothing to do with statue construction or changes in carrying capacity (Hunt & Lipo 2011a; Lipo et al. 2013).

One persistent "collapse" claim is that prehistoric Rapa Nui populations engaged in intense warfare when resources became scarce in late prehistory (Bahn & Flenley 1992; Diamond 1995, 2005; Flenley & Bahn 2003). The island, however, lacks evidence of systematic warfare. There is no evidence, for example, for defensive structures that are common islands on other islands in the Pacific with known traditions of warfare. Instead, claims of prehistoric warfare are largely based on oral traditions recorded in the 20th century (e.g., Routledge 1919). Unfortunately, these accounts have an unknown relation to prehistory and, as Metraux (1940) has argued, are likely recent introductions.

One lingering line of empirical evidence that is used infer prehistoric warfare is the presence of *mata’a* (Diamond 2005; Metraux 1940). *Mata’a* are flaked obsidian tools with narrow stems and wide blades. Overall, their form is similar to stemmed artifacts found on other Polynesian islands such as New Zealand, Pitcairn and the Chatham Islands (Balfour 1917; Metraux 1957: 232; Skinner 1958) as well as on New Britain, Papua New Guinea (e.g., Araho 1997; Specht *et al.* 1988; Torrence *et al.* 2009a; Torrence *et al.* 2009b; Torrence et al. 2013). On Rapa Nui, the vaguely “spear like” shape of *mata’a* combined with oral traditions have led to assumptions that *mata’a* were weapons and thus are linked to the presumed “collapse” (e.g., Diamond 2005).

Here, we explore whether evidence from the shape of *mata’a* can be used to infer their use as weapons of warfare or some other potential range of functions. Using an image database of 423 intact *mata’a* sampled from 4 collections, we conduct a quantitative morphometrics analysis: an approach that treats shape as a continuous property of objects rather than nominal categories (Bookstein 1982; Bookstein *et al.* 1985; Bookstein 1997; Cardillo 2010; Kendall 1989). Morphometrics allows one to use multivariate analyses and ordination approaches to test if particular clusters of shapes map to particular locations, environments, or source material. In this way, the approach can lead to the evaluation of hypotheses regarding the potential use environments for these intriguing artifacts*.*

# Approach

*Mata’a* have been noted since the earliest European visitors described the island. In 1774, members of Cook's expedition to the island, for example, commented that the islanders “had lances or spears made of thin ill-shaped sticks, and pointed with a sharp triangular piece of black glassy lava” (von Saher 1990: 35). Many of these early visitors assumed *mata’a* were "spears" simply due to their resemblance to European varieties rather than any direct observation of their use. Scars on Rapanui noted by early European observers may have been the result of *mata’a* use though there is no direct evidence that the use was lethal. In his voyage to Rapa Nui in 1770, Captain Don Felipe González (Haedo & Roggeveen 1908:99), for example, remarked that "they [Rapanui] possess no arms, and although in some we observed sundry wounds on the body, which we thought to have been inflicted by cutting instruments of iron or steel, we found that they proceeded from stones, which are their only [weapons of] defence [sic] and offence, and as most of these are sharp edged they produce the injury referred to." Thus, it is possible that *mata’a* were used as cutting implements but not necessarily as tools for killing.

To avoid making assumptions about function based on what *mata’a* resemble, we argue that we can examine the physical evidence of *mata’a* for clues as to their prehistoric use. The physical features of *mata’a* shapes and configuration should reflect the range of interactions that occurred between the artifact and the environment. Constraints in shape relative to areas that are free to vary inform us on the parts of object that have performance criteria. Studying shape variability, therefore, provide a means of evaluating hypotheses about use.

*Mata’a* are one of the most numerous shaped artifact classes on Rapa Nui (Figure 2). Overall, they vary in size, but average 6 to 10 cm in width and length. Technologically, they are formed from unifacial flakes created by hard hammer percussion on obsidian cores quarried from one of the island's four obsidian sources. Most of the shaping of *mata’a* occurs during the creation of a stem through unifacial flaking. Lenticular in cross section, the stem is formed from one of the lateral margins of the original flake while the blade constitutes the remaining distal and opposite lateral edges. Overall, the shape of the parent flake dominates the blade shape.

Notably, the shape of mata’a are not consistent with the lanceolate shapes usually associate with weapons where the goal of the attacker it to pierce the body of another and damage internal organs and incur bleeding. Instead, of strongly being designed to optimize lethal damage, we find a wide array of shapes: researchers have noted that *mata’a* blades take a variety of shapes that range from rounded to sub-angular to angular to complex (Mulloy 1961). Early attempts to assign *mata`a* shapes to ethnographic categories using Rapanui words (i.e., Routledge 1919) largely failed since clear divisions between shapes and use can be identified. Later attempts to construct systematic classifications have also focused on identifying types based on characterizations of overall shape (e.g., Mulloy 1961). None of these classification efforts produced meaningful categories. Mulloy (1961: 151), for example, argued that “no significant clustering or correlations could be extracted.... the material represents a continuous range of variation without objective natural order, and that the only classification possible must involve the subjective selection of ideal types from infinite series of possibilities, and the arbitrary reference of intermediate forms to one or another of these.” Mulloy concluded that manufacturing procedures dictated differences in overall shape of *mata’a* and were best explained by chance. As lethal stabbing implements, this variability would have significant negative impacts to the performance of any example.

In studying artifact shape, we must recognize that the overall shape not necessarily connected to function. Artifact forms are the result of processes including technological constraints of the material, performance aspects that depend upon the range of environments in which the object is used, as well as simple idiosyncratic variability related to the manufacturer and the process of production. Thus, while overall shape is not equivalent to function, dimensions of objects may have the potential to affect the relative performance and thus will be shaped by natural selection (Dunnell 1978). In the case of *mata’a,* it is the blade that interacts with the environment and that is directly related to its performance in cutting, puncturing or scraping. Rather than have a specific shape indicating a narrow range of uses, *mata’a,* have significant variability in blade shape much of which can be explained as the contingent results of manufacture rather than specific design decisions (Bollt *et al.* 2006). Studies of use-wear on *mata’a* support this notion as the evidence points to their use in a variety of ways include scraping and cutting (Church & Rigney 1994; Church & Ellis 1996).

A recent study of *mata’a* shape at the scale of assemblages using deterministic frequency seriation as a means for examining how class frequencies changed over space and through time shows that *mata’a* forms vary in a remarkably continuous fashion (Lipo *et al.* 2010). The seriation results suggest that at least some of the variability in *mata’a* form, particular shoulder angles and stem shape, was inherited through the social learning between individuals. The evidence also indicates that the stem portion of the shape variability in *mata’a* form is not directly associated with *mata’a* performance in its use environment but simply a feature of the individual making the object.

In our current analysis, we focus on determining whether the blade variability can be used to identify specific functional classes in which there were performance constraints on the shape of the distal portion of the blade. Thus, we focus on studying *mata’a* variability in the blade portion of the *mata’a* relative to the stem. We assume that the point at the center of the stem where it meets the blade can be held constant to allow for comparisons. We also assume that due to performance the functional aspects of the tool will result in shape variability that is more constrained than aspects of shape that have no performance effects and are effectively stylistic attributes (Lipo et al. 2012). Constraints related to performance are assumed to sort shape variability in proportion to the benefits/drawbacks. Based on this notion, we hypothesize that:

* If *mata’a* are systematic weapons of warfare, the distal end of the artifact will be constrained in its shape.
* If *mata’a* are systematic weapons of warfare, the distal end of the artifact will show a tendency towards a spear-like shape that is consistent with the penetration of enemies or prey. If *mata’a* are not weapons, there will be no such shape restriction of the distal end of the tool.

# Methods and Data

In order to test these hypotheses, we begin by assuming that the blade portion of *mata’a* shape is a functional element (*sensu* Dunnell 1978), the portion of the artifact that interacts with the environment. Consequently, our interest is on those aspects of shape that potentially affect function and thereby come under natural selection. The task of explaining variability in shape consists of identifying selective pressures that affect the performance of shape and to determine whether their magnitude is sufficiently great to impact fitness. The greater the selective pressures on performance, the more constraint we would expect in those aspects of shape. If the effect on function and performance is sufficiently small, then other forces such as technological (i.e., material source, manufacturing steps, etc.) or stylistic (stochastic or neutral) processes may be posited as having played a role in structuring the shapes of *mata’a*, as well as when and where they occur in the archaeological record. In aspects of shape not under selection, we would expect to see a greater range of variability. It is possible, however, that not all *mata’a* instances were used in the same way. If *mata’a* shape is influenced by more than one function, either contemporaneously or over time, then the selective context will differ and thus the “cause” of *mata’a* shape should vary. In this scenario we would expect to see modal patterns of *mata’a* shape where outline variants form statistically-distinguishable groups.

To evaluate these ideas, we used morphometrics, a quantitative analysis of form in terms of shape and size, in two or more dimensions (Bookstein 1982; Bookstein *et al.* 1985; Bookstein 1997; Cardillo 2010; Kendall 1989; Rohlf 1990). Morphometric approaches have advantages over traditional studies of shape using global shape descriptors, or lengths and ratios of lengths. First, morphometrics avoids the problem of nominal shape (e.g., "triangular", "square", "round") by transforming the overall shape into independent, quantitative variables. Then, with techniques available for standardizing position, scale and rotation, morphometrics allows one to explore, compare and test for differences in the shape (form minus size) of artifacts.

With roots in biology, the earliest form of morphometrics focused on identifying the location of specific landmarks (e.g., Thompson 1917). A landmark approach requires defining features that are to be examined as to how they relate to each other. In the case of artifacts such as *mata’a,* there are few consistent landmarks to hold constant other than perhaps the distal and proximal ends. One can also conduct an analysis of what is known as "semi-landmarks," a fixed number of regularly positioned points around the outline of an object (Bookstein 1997; Gunz & Mitteroecker 2013). Both approaches to measuring shape make use of the relative positions between all points (Bookstein 1991; 1997). *Mata’a* shapes are clearly in the second case, and we used outline analysis on the basis of semi-landmarks.

For our morphometrics analyses, we used *Momocs1* v0.99 (<http://CRAN.R-project.org/package=Momocs>), an R package (R Core Team 2015) developed by Bonhomme (2012; Bonhomme et al. 2014).

# Data

Our dataset consisted of planview photographs of artifacts that we selected randomly from whole specimens available in museum and field collections (Table S1 and S3). We used a collection of 118 *mata’a* from 4 locations that are currently housed at the P. Sebastian Englert Museum on Rapa Nui. These *mata’a* were collected by Sebastian Englert, William Mulloy and other researchers and comprise all whole *mata’a* that were available for examination in the museum. For comparison, We also included 8 *mata’a* published by Heyerdahl (Heyedahl & Ferdon 1961a) and 6 f *mata’a* that Hunt and Lipo (2008)photographed during pedestrian surveys of land parcels on the south coast of Rapa Nui. Finally, we included photographs of 291 objects that are housed Bishop Museum, Honolulu, Hawai'i. Mulrooney and colleagues (2014) took photos of these *mata’a* during their study of obsidian sourcing via pXRF. Despite the fact that we do not have specific provenience information for these artifacts, we are able to use this collection to examine potential shape variability that might vary as a function of obsidian source (Figure 3). This shape variability could be potentially caused by systematic material differences or by the differential use of *mata’a* at different locations. In total, our data set includes 423 *mata’a*. Based on bootstrap estimates of basic metrics (Figure S1), this sample size is large enough to adequately characterize shape and overall *mata’a* configuration.

To ensure that the shapes were directly comparable, we aligned scaled and oriented photos of *mata’a* at the point where the midpoint of the stem meets the blade. We converted the images to binary format and used TPSDig software (Rohlf 2014) to create outlines of each *mata’a* consisting of 200 sets of X-Y coordinates located equidistantly along the perimeter of each artifact (Figure 4).

Simple metrics of length and width (Figure 5) reveal a single distribution of these objects without clear-cut size modes. A more direct means of evaluating shape variability is accomplished by superimposing *mata’a* outlines (Figure 6). To quantitatively analyze these data, we calculated the distance to the perimeter in one-degree intervals for the 360-degree perimeter from a reference point where the center of the stem where it intersects the blade. This process enables us to examine where shape varies and where it is more constrained (Figure 7). Based on the 95% confidence intervals for the radial distances, *mata’a* shape varies the least at the point where the stem intersects the blade. The systematic shape of the stem likely reflects the manner in which *mata’a* were held or hafted to a shaft. Stem length, however, varies significantly as does the overall shape and length of the distal blade edge. Importantly, the portions of the *mata’a* shape related to its use and interaction with the environment widely vary.

# Morphometric Analyses: Elliptic Fourier Analysis

With morphometrics, we can exam the degree to which shape variability may form groups that are related to specific functions using elliptical Fourier-based analyses (Bonhomme 2014; Claude 2008; Kuhl & Giardina, 1982; Giadina & Kuhl 1977). Elliptical Fourier approaches treat shape as a periodic function that can be fitted using a sum of simple trigonometric functions. These simple functions are harmonics of one another. Lower harmonics provide approximation for the coarse-scale trends in the original periodic function while the high-frequency harmonics fit its fine-scale variations (Figure 7, Supplemental Text).

With elliptical Fourier characterizations we can examine *mata’a* shapes to determine if there are clusters that might distinguish sub-groups from each other. Figure 8 presents the position of *mata’a* shapes on a factorial map with shapes reconstructed from the first two principal component axes derived from the Fourier values. Overall, there no discrete shape groups as *mata’a* vary continuously in their outlines. There are no subsets of lanceolate-shaped *mata’a* that might be seen as distinctive from other groups. Instead, we see a wild mix of shapes without any modes. These results supports the notion that *mata’a* have no single function for which blade shape affects performance. Consistent with observations of use-wear on the blade edges (e.g., Church 1998; Church & Rigney 1994; Church & Ellis 1996; Stevenson & Cardinali 2008: 107), it is likely that this means that *mata’a* edges must only be sufficient for generally cutting and scraping.

We can also explore whether there are systematic differences between the locations from which *mata’a* are found or between the obsidian sources used to make the artifacts. In our analyses, we used *mata’a* from 4 sites on Rapa Nui (Table S1 and S3). Figure 9 presents the distribution of sets of *mata’a* from multiple locations across the island (Figure 2). The graph includes the 50% Gaussian confidence ellipses for each of the 4 sites and the underlying grid represents the morphological space based on the first two principal components. The overlap of the groups indicates that the shapes from each of the sites cannot be distinguished. The same conclusion can be drawn from the analysis of the shape variability relative to obsidian source (Figure 10). Overall, there is no evidence that *mata’a* blade shape was constrained due to functional performance.

# Comparison with stemmed tools from other Pacific Islands

The *mata’a* of Rapa Nui share shape similarity with stone tools found on other islands across the Pacific. On New Britain in Melanesia, for example, Torrence (2009a, 2009b, 2013) has described stemmed obsidian tools that are similar to *mata’a*. Torrence (see also Kononenko 2012) argues that these tools may have been used for a range of activities including tattooing and ritual scarification. An additional but limited comparison can be made with Pitcairn Island, where a few stemmed lithic tools have been found (Heyerdahl & Ferdon 1961b). Pitcairn Island is a remote Eastern Polynesian island that is located ca. 1900 km to the west of Rapa Nui. Historically-related Polynesian populations inhabited the island, though it was abandoned during prehistory. Stemmed lithics of chert known as locally as *mataa* are also found on the Chatham Islands and on New Zealand (Jones 1981).

As a comparison for our study, we generated outlines of examples of stemmed lithic tools from published images using the same procedure as for Rapa Nui (Table S5). Our elliptic Fourier analyses of shape variability required 13 harmonics to adequately characterize the shape of all of the stemmed artifacts (Figure 11). While the sample sizes of the non-Rapa Nui assemblages are small, when we compare the shapes of Rapa Nui *mata’a* with those other objects, we find that the Pitcairn Island stemmed artifacts have overall shapes that are quite distinct. While we cannot rule out the possibility that the Pitcairn examples are a few extremely long and pointed shapes that happen to have been collected from a much wider array of variability, these shapes are certainly more consistent with hafted tools for hunting or weapons. New Zealand *mataa* are similar but have substantially thicker stems than the Rapa Nui artifacts. Jones (1981) suggests that this might reflect tools that are hafted with the edge perpendicular to the shaft such as an adze. Given their chert composition and relatively steep edge angles, this shape might be well suited for activities such as woodworking.

The New Britain artifacts, on the other hand, show a wide array of features that are more like the ones from Rapa Nui. Based on this comparison, it is conceivable that one of the Rapa Nui *mata’a* functions reflect the same kinds of uses that are thought to characterize the New Britain tools. Tattooing is known from Rapa Nui through ethno-historic observation (Huish 1839: 77; Métraux 1940; Thomson 1891: 22) and as markings on the prehistoric *moai* (Lee 1992). It would not be surprising that at least some of the *mata’a* objects were used in tattooing and scarification practices.

# ConclusionS

Our investigation of shape variability for Rapa Nui *mata’a* fails to support hypotheses about the potential use of these objects as weapons – so-called "weapons of mass destruction" (Keegan 1993). Instead, we gain more support for the use of these object in cultivation and domestic activity as suggested by use-wear analyses (Church & Rigney 1994; Church & Ellis 1996). While the tale of prehistoric Rapa Nui collapse and self-destruction remains popular, the evidence to support this claim is non-existent. In addition to a lack of defensive structures and skeletal evidence for lethal violence (Hunt & Lipo 2011a when we take a careful look at the shape of *mata’a* we simply do not see evidence that these classes of artifacts represent lethal weapons (see also Ingersoll & Ingersoll 2013). There appears to have been no systematic performance requirements that strongly influenced the blade shape. Other than having sharp edges, *mata’a* are no more lethal than any other kind of rock. Indeed, as documented in European accounts of Rapa Nui, rock throwing from high points is the primary way in which native Rapanui fought off intrusion by Europeans and is far more likely to represent potential lethal weapons than *mata’a* (e.g., Roggeveen's 1722 visit, Eyzaguirre et. al 1908). It is important to note that this conclusion does not mean that prehistoric populations did not experience violence, only that this violence does not appear be related to systemic warfare where performance as lethal weapons would be paramount.

Our conclusion that *mata’a* had more than one function is not surprising and it is essential to resist the notion that any object is imbibed with an inherent function (Dunnell 1978). Instead, we measure function on the empirical variability for assemblages of objects (Dunnell *et al.* 1976). In the case of *mata’a* the wear patterns and distribution in rock mulch suggest that at least some of these objects were employed in cultivation. We also cannot rule out that some *mata’a* may have been used for general domestic and ritual activities such as tattooing and scarification practices. The latter function is consistent with observations of healed scars made by Spanish visitors in AD 1770 (Eyzaguirre *et al.* 1908).

It is unfortunate that in the case of Rapa Nui the myth of its prehistory continues to persist despite the lack of evidence to support it. In Rapa Nui archaeology, tradition has long trumped empirical inquiry as can be seen in claims about *mata’a* as weapons rather than a part of subsistence and social dimensions of prehistoric Rapa Nui. In the case of Rapa Nui, getting the correct answer is far from a trivial academic exercise. The island's prehistory is often used as an exemplar of the consequences of ignoring the impacts humans make on their environment. In a sense, the assumptions about *mata’a* have led to potentially erroneous conclusions. United Kingdom Prime Minister Margaret Thatcher, for example, famously used Rapa Nui as a warning in a 1989 presentation to the General Assembly of United Nations (e.g., Thatcher 1989). Similarly, *mata’a* have been used as examples of mass effect "weapons" in a study of terrorist tactics (Rasmussen & Hafez 2010). Given the contemporary importance that Rapa Nui has in guiding our concerns for our future, we owe it to ourselves to make certain that we fully understand the prehistory of the island and that our understanding is based on well-documented and thoroughly researched evidence.

# FOOTNOTES

*1Momocs* builds upon techniques developed by Claude (2008) and reviewed by Bowman (2009). Bonhomme incorporated functions from Claude's work into an integrated framework and a standalone R package. The package's vignette *A* *Graphical Introduction to Momocs and Outline Analysis Using R* (Bonhomme 2012) provides an extensive description of the functions of the package. All of the R code and data for this project is freely available at <https://github.com/clipo/mataaMorphometrics>.

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Figure 1. Pacific island locations mentioned in the text.

Figure 2. Examples of *mata’a* from Rapa Nui. These *mata’a* are part of the collections at the P. Sebastian Englert Museum, Hanga Roa, Isla de Pascua.

Figure 3. Locations of *mata’a* collections and obsidian sources on Rapa Nui, Chile.

Figure 4. Measurement process used to generate outline coordinates for each *mata’a* in the study. (A) First, we took a scaled digital photo is taken of the object. We also ensure that all images are resized so that they are equivalent in scale. (B) Second, we isolated the outline of *mata’a* from the background using TPS Dig software (Rohlf 2014). (C) Along the perimeter of the artifact, we placed 400 semilandmarks and recorded their x- and y-coordinates. We then use these coordinate data in the morphometric analyses.

Figure 5. Lengths and widths of all Rapa Nui *mata’a* in the study. Overall, the lengths and widths are normally distributed with only a single mode in each dimension.

Figure 6. Comparison of *mata’a* shapes from Rapa Nui. (A) Superimposed outlines of Rapa Nui *mata’a*. To make the comparisons, we aligned all *mata’a* at the center point of the stem where it meets the blade. (B) Variability in *mata’a* shape shown with mean and 95% confidence intervals. The 95% confidence intervals are shown with 10x exaggerated differences between the values to illustrate areas with greater variance versus those with more constrained shape. Here, the area at the base of the stem where it meets the blade is the most constrained portion of *mata’a* shape while the stem length and blade are more variable.

Figure 7. Elliptic Fourier analysis is based on the sum of harmonic trigonometric functions, fitting separately x and y coordinates, that together define ellipses in the plane. Five harmonics are here shown at four locations on the original outline of a *mata’a*. As the number of harmonics is increased the reconstruction better approximates the original shape outline.

Figure 8. Results of the Principle Component Analysis (PCA) conducted on the elliptic Fourier descriptions Rapa Nui *mata’a* shapes*.*  This figure shows the first two principal components (PC1 and PC2 are on the x- and y-axis, respectively). Each point represents a *mata’a* described in terms of its shape along these two components. The short lines along each axis show the distribution of the points relative to the individual components. The bar graph at the bottom indicates the amount of shape explained by the first two components relative to the first five components. The gray shapes in the background represent the shape explained by the two components. In the upper left hand corner of the graph are objects that are relatively long and thin while the bottom right hand corner represents objects that are primarily round.

Figure 9. Rapa Nui *mata’a* shapes grouped by site locations arrayed on the first two principal components of the elliptic Fourier shape descriptions. The *mata’a* are shown with the 99% confidence ellipses for the site location groups. MANOVA conducted on the PCA results (Table S2) show that while there is significant overlap between all of the groups, there are some differences in the overall shapes of a couple of sets. The Orongo, Orito and Rano Kau set are significant different from the group of *mata’a* from unknown locations across the island, a set which comprises the Bishop Museum collection. These differences are potentially related to collection bias. This bias may have been introduced by the casual collectors who picked up specimens with expectations as to what a *mata’a* ‘should’ look like. The relative small differences between the shapes of the Orongo and the Rano Kau assemblages is likely explained by the stylistic differences that are demonstrated in seriation analyses of mata’a shape classes (Lipo et al. 2010).

Figure 10. Rapa Nui *mata’a* shapes grouped by identified obsidian sources relative to the first two principal components of the elliptic Fourier shape descriptions. The *mata’a* are shown with the 99% confidence ellipses for compositional groups. MANOVA conducted on the PCA results (Table S4) show that while there is significant overlap between all of the groups, there are some differences between Orito obsidian *mata’a* and the assemblage of *mata’a* for which we have no obsidian source information. These differences may be attributed to the fact that the *mata’a* that have obsidian sources identified were made by casual collectors with specific shapes in mind.

Figure 11. Variability in shapes among stemmed lithic shaped objects from Rapa Nui, New Britain, New Zealand, Chatham and Pitcairn Islands. The artifacts are shown grouped by island and arrayed against the first two principal components of the elliptical Fourier descriptions. Results of MANOVA for the large assemblages (Table S6) and Wilcoxon rank sum test (Table S7) for the small assemblages that there are no significant differences between the shapes of the assemblages except for the comparison of the Pitcairn and the Chatham island examples.

# SUPPLEMENTARY INFORMATION

Our measured outlines are composed of 200 points evenly spaced along the outline of the objects. *Momocs* interpolates between points to locate distances from centroids at even intervals. In addition, since all measurements are based on georeferenced coordinates, planimetric measure (such as width or length) can be calculated. Additional image analysis techniques to isolate object outlines point to the strong potential for automation of the measurement process, greatly increasing the ability to characterize large assemblages. With large numbers of measures of radial distances made relative to the *mata’a* centroids, we then calculate a statistical summary for each angle to assess variability in relative dimensions.

In morphometrics, Fourier treats closed outlines as periodic functions. If you start somewhere on the outline and follow it, you will pass again and again by the same starting point and thus periodic functions can describe this outline. These functions can use a variety of descriptive data for the outline: the distance of any point on the outline to the centroid of the shape, the variation of the tangent angle for any point, or the (x/y) position on the plane (Rohlf & Archie 1984). For an outline shape, a periodic function is obtained and can be decomposed (and thus described) by Fourier series.

Fourier series, however, work on continuous functions. Since in practice shape is measured on a finite number of discrete points on a plane (in our case, x/y coordinates), a discrete equivalent to Fourier series is used in morphometrics. A given number of points called pseudo-landmarks have to be sampled along the outline before computing shape analysis. All Fourier decomposition then result in a harmonic sum of trigonometric functions associated with harmonic coefficients. They are (usually) normalized to remove homothetic, translational or rotational differences between shapes. Two or four coefficients, depending on the approach used, are obtained for each calculated harmonic and can then be considered as quantitative variables. The geometrical information contained in the outlines are thus quantified and can be analyzed with classical multivariate tools.

To conduct Fourier analysis, we must estimate the number of necessary harmonics after examining the spectrum of harmonic Fourier power. The power is proportional to the harmonic amplitude and can be considered as a measure of shape information. As the rank of the harmonic increases, the power decreases and adds less and less information. We can evaluate the minimum number of harmonics required to best approximate the shape. In the case of the *mata’a* and using x/y position for points on the outline as the data set, 12 harmonics provide a good reconstruction of the overall shape (Figures S2 and S3).

Table S1. Rapa Nui *mata’a* included in analyses by site and by repository (N=423).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | *Site* | | | | | |
|  |  | Ahu Tautira | Orito | Orongo | Rano Kau | Parcelas | Unknown |
| *Collection* | Bishop Museum | 0 | 0 | 0 | 0 | 0 | 291 |
| P. Sebastian Englert Museum | 25 | 31 | 29 | 33 | 0 | 0 |
| Heyerdahl & Ferdon 1961a | 0 | 0 | 0 | 0 | 0 | 8 |
| Field Surveys (Hunt & Lipo 2006) | 0 | 0 | 0 | 0 | 6 | 0 |

Table S2. Results of MANOVA for Rapa Nui *mata’a* shapes grouped by site location.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| *Comparison* | *Pillai Statistic* | *Approximate F* | *Degrees of Freedom* | *p-value* |
| Ahu\_Tautira - Orito | 0.06193215 | 0.2420769 | 22 | 0.957466644 |
| Ahu\_Tautira - Orongo | 0.05560218 | 0.1962527 | 20 | 0.974104678 |
| Ahu\_Tautira - Parcela | 0.2504351 | 0.5011609 | 9 | 0.793418058 |
| Ahu\_Tautira - Rano\_Kau | 0.35941869 | 2.1508146 | 23 | 0.08600363 |
| Ahu\_Tautira - Unknown | 0.06921958 | 1.9211541 | 155 | 0.080653113 |
| Orito - Orongo | 0.20782605 | 0.9619464 | 22 | 0.473111612 |
| Orito - Parcela | 0.35290287 | 0.9998323 | 11 | 0.471607994 |
| Orito - Rano\_Kau | 0.34630248 | 2.2073313 | 25 | 0.076044588 |
| Orito - Unknown | 0.1189607 | 3.5331059 | 157 | 0.002621205 |
| Orongo - Parcela | 0.24543826 | 0.5963331 | 11 | 0.728110499 |
| Orongo - Rano\_Kau | 0.38662672 | 2.6263692 | 25 | 0.040967992 |
| Orongo - Unknown | 0.11393999 | 3.3648169 | 157 | 0.003790983 |
| Parcela - Rano\_Kau | 0.4768608 | 1.9749971 | 13 | 0.142954022 |
| Parcela - Unknown | 0.04653588 | 1.1795064 | 145 | 0.320454247 |
| Rano\_Kau - Unknown | 0.11683632 | 3.4837141 | 158 | 0.00291422 |

Table S3. *Mata’a* included in analyses by obsidian source and collection.

|  |  |  |
| --- | --- | --- |
|  |  | *Collection* |
|  |  | Bishop |
| *Obsidian Source* | Motu Iti | 5 |
| Orito | 279 |
| Rano Kau | 7 |

Table S4. Results of MANOVA for Rapa Nui *mata’a* shapes grouped by obsidian source.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| *Comparison* | *Pillai Statistic* | *Approximate F* | *Degrees of Freedom* | *p-value* |
| Motu\_Iti - Orito | 0.0098 | 0.2702 | 137 | 0.9287 |
| Motu Iti – Rano Kau I | 0.5583 | 0.7584 | 3 | 0.6338 |
| Motu Iti – Unknown | 0.0666 | 0.9136 | 64 | 0.4779 |
| Orito – Rano Kau I | 0.0538 | 1.5801 | 139 | 0.1695 |
| Orito - Unknown | 0.0996 | 4.4237 | 200 | 0.0007 |
| Rano Kau 1 - Unknown | 0.0387 | 0.5013 | 62 | 0.7741 |

Table S5. Stemmed lithic tools from island locations in the Pacific (N=24).

|  |  |  |
| --- | --- | --- |
| Island | Number | Source |
| Chatham | 8 | Jones 1981 |
| New Britain | 12 | Torrence 2009a, 2009b, 2013 |
| New Zealand | 2 | Jones 1981 |
| Pitcairn | 2 | Heyerdahl & Ferdon 1961b |

Table S6. Results of MANOVA for Rapa Nui *mata’a* shapes grouped by island.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| *Comparison* | *Pillai Statistic* | *Approximate F* | *Degrees of Freedom* | *p-value* |
| Chatham - New\_Britain | 0.6015 | 0.1886 | 1 | 0.9497 |
| Chatham - Rapa\_Nui | 0.0407 | 1.0918 | 206 | 0.3702 |
| New\_Britain - Rapa\_Nui | 0.0532 | 1.4606 | 208 | 0.1734 |

Table S7. Wilcoxon rank sum test of Rapa Nui *mata’a* shapes grouped by island.

|  |  |  |
| --- | --- | --- |
| *Comparison* | *W score* | *p-value* |
| New Zealand - New Britain | 17 | 0.4108 |
| New Zealand - Chatham | 14 | 0.1497 |
| New Zealand - Pitcairn | 4 | 0.3333 |
| New Zealand - Rapa Nui | 725 | 0.0819 |
| Chatham - New Britain | 39 | 0.5116 |
| Chatham - New Zealand | 2 | 0.1497 |
| Chatham - Pitcairn | 16 | 0.0495 |
| Chatham - Rapa Nui | 1606 | 0.0807 |

SUPPLEMENTAL FIGURES

Figure S1. Sample size and *mata'a* parameter estimation. By repeatedly resampling the collection with an increasing number of samples until we reach twice the original sample size while also comparing changes in the 95% confidence intervals of length and width for each set of resampled assemblages, we can assess the degree to which metrics change with increasing samples. The sample size (N=423) shown via the dotted lines) of *mata'a* appears to be sufficient to estimate variability in the basic shapes.

Figure S2. *Mata’a* included in the current analyses. The 5 colors indicate the collection locations on Rapa Nui (Blue=Ahu Tautiri, Green=Orito, Yellow/Green=Orongo, Orange=Rano Kao, Red=Location only known to the level of the island, Yellow=Parcela).

Figure S3. *Mata’a* reconstructed from different numbers of harmonics. Twelve harmonics provide a satisfactory reconstruction.

Figure S4. Cumulated harmonic Fourier power calculated from Rapa Nui *mata’a*. The 12 first harmonics gather nearly 100% of the harmonic power. Maxima, minima and medians are also plotted.

SUPPLEMENTAL TABLES

Table S1: Rapa Nui *mata’a* included in analyses by site and by repository (N=423).

Table S2. Results of MANOVA for Rapa Nui *mata’a* shapes grouped by site location

Table S3: *Mata’a* included in analyses by obsidian source and collection.

Table S4. Results of MANOVA for Rapa Nui *mata’a* shapes grouped by obsidian source.

Table S5. Stemmed lithic tools from island locations in the Pacific (N=24).

Table S6. Results of MANOVA for Rapa Nui *mata’a* shapes grouped by island.

Table S7. Wilcoxon rank sum test of Rapa Nui *mata’a* shapes grouped by island.