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Standardization of ceramic shape: A case study from the Iron Age pottery from northeastern Taiwan

--Manuscript Draft--

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Abstract:	The emergence of ceramic specialization in prehistoric societies is often linked to shifts in the complexity of social structures, because standardized ceramic production can reflect craft specialization and the presence of elite control. Previous work on identifying specialization relies on typological or linear metric analysis. Here we demonstrate how to investigate ceramic standardization by analyzing outlines of ceramic vessels. Outline analysis is useful because, unlike more commonly-used landmark analysis methods, it can effectively quantify shape differences for objects that lack distinctive measurement points needed for landmark analysis. We demonstrate this method using pottery from Kiwulan, a large multi-component Iron Age site (AD 1350-1850) in northeastern Taiwan. To measure ceramic specialization, we quantified pottery standardization by analyzing shape variables with reproducible geometric morphometric methods. We computed coefficients of variation (CVs) for shape coefficients obtained by elliptical Fourier analysis to test for shape standardization. We found significant differences in pottery shape and shape standardization that indicate changes in pottery production resulting from contact with mainland Han Chinese groups in northeastern Taiwan. Our case study, which includes an openly available research compendium of R code, represents an innovative application of outline-based methods in geometric morphometry to answer the anthropological questions of craft specialization.
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	Josef Wilczek josef.wilczek@hotmail.com A researcher who works on pottery using Geometric morphometrics methods
	Selden Z. Robert, PhD Research Associate, Stephen F. Austin State University zselden@sfasu.edu A researcher of material culture and prehistory, especially working on morphological variation in the archaeological record
	Radu Iovita, Ph.D Assistant Professor, New York University iovita@nyu.edu A Paleolithic archaeologist working on stone artifacts using elliptical Fourier analysis

Opposed Reviewers:	
Response to Reviewers:	

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13 August 2020

Dear Dr. Howard,

Thank you for forwarding to us the reviewers' comments on our submission. Sorry for our slow reply. We were very pleased to see the positive feedback from the reviewers. We found all the comments most useful, and have diligently followed all their suggestions to improve our paper.

In our document of response to reviewers, we highlighted the actionable comments the reviewers in red, and indicated our responses by these symbols >>>

Thanks again,

Li-Ying Wang

Response to Reviewers

In our detailed reply below, we highlighted the actionable comments from you and the anonymous peer reviewers in red, and indicated our responses by these symbols >>>

Reviewer 1

I appreciate the opportunity to review this manuscript. I found it to be a novel application of geometric morphometrics couched within craft specialization, and am happy to recommend it for publication with minor revisions. I am providing my edits of the manuscript below, with the intention that you will share both that document—and this one—with the authors. Please leave my name and email address appended to this review, as I would be happy to answer any questions that the authors may have regarding my comments.

The authors are to be applauded for their efforts to ensure that their results are replicable, and should JAS:Reports employ the Open Data/Open Material badges from the Open Science Framework, you should consider this manuscript eligible for both.

In my comments, I noted that I have used mathematically-defined landmarks and semilandmarks in my work. These are rooted in the work of Birkhoff (1933) and Rice (1987), where one can find examples of characteristic points and tangents that might have utility in future analyses. I would advise against stepping into some form of debate regarding EFA and landmark-based approaches, and focus upon the logistics of the case study. That being said, I do think that you have a dataset that you could use to test that proposition, should you be so inclined. I would also be sure to cite the earliest effort to use EFA in closed form within an archaeological framework (Gero and Mazzullo 1984), and include mention of how the field has progressed/advanced since that time.

>>> We thank Dr. Selden for his suggestions for focusing on the studies of EFA. We have removed the debate regarding EFA and landmark-based approaches, and focused on the logistics of the case study. We have expanded the background of EFA (pp. 4) to include the reference (Gero and Mazzullo 1984) and others to present how this field has progressed. We have reviewed the works that have used EFA in archaeology, and justify the use of EFA for our case study.

I would point out, perhaps in your figure caption (Figure 4), that the differences illustrated in your splines—between the occupations—are significant (as you subsequently demonstrate in Table 1).

>>> We appreciate Dr. Selden's observation on the figure. We have revised the caption of figure 4 to point out the significant differences in average vessel shapes across periods, and mentioned also in the main text to make the sentences clear and consistent with the results in Table 1.

Many of our colleagues that employ GM in their work routinely discuss standardization. That said, those efforts are not regularly incorporated into discussions of craft specialization, but this does not preclude their use within a discussion that outlines how those efforts have been framed, and what methods were used in their analyses. I encourage the authors to briefly summarize GM studies that have employed discussions of standardization, and consider the various metrics that others have used in their work (see Archer et al. 2015; Buchanan et al. 2018; Doyon 2019; Eren et al. 2015; Kuzminsky et al. 2016; Natahi et al. 2019; Okumura and Araujo 2014; Perez 2007; Presnyakova et al. 2018; Selden Jr. 2018a; Selden Jr. et al. 2020; Selden Jr. et al. 2018; Smith and DeWitt 2016; Topi et al. 2017). Those citations listed above are by no means exhaustive, but should provide a suitable starting point.

>>> We appreciate Dr. Selden's suggestion and the reading list related to standardization using GMM. We have added a paragraph (pp. 3) to review those studies and summarize how they study and discuss shape standardization case by case. We have also incorporated the analysis of metric attributes in our work, body diameter of ceramics, to discuss ceramic standardization (pp. 12-13).

In the limited discussions of standardization and craft specialization that employ GM methods, I find it regrettable that archaeologists are not employing morphological disparity instead of CV. In my opinion, since morphological disparity was designed to be a component of the GM toolkit, it is a more suitable approach when using GM (shape) data. That said, I admit that I am unaware of any study that has compared the results of linear measurements using CV and shape measurements using morphological disparity. I regularly use this measure in my own work (Selden Jr. 2018a, 2019; Selden Jr. et al. 2020; Selden Jr. et al. 2018), and have found it to be a useful tool for considering potential standardization for vessel (and stone tool) shape and size.

>>> We appreciate Dr. Selden's suggestion of morphological disparity and size analysis. We have employed a test of morphological disparity, which demonstrates the same results as the CV test we used. We include the result in the "Discussion" section (pp. 14) and the analysis script is available with our supplementary materials here: https://doi.org/10.17605/OSF.IO/ABVGF

The fact that GM methods isolate size provides analysts with a means of analyzing size differences, and considering differences not only in shape, but form (shape + size), and I encourage the authors to include an analysis of size in this piece. There are several approaches to analyzing form, which have been useful in better characterizing morphological convergence and divergence in both ceramics (Selden Jr. 2018b, 2019) and lithics (Selden Jr. et al. 2020).

>>> We have conducted linear regression between shape and size, represented by body diameter, and found that the diameter generally varies with shape. We attempted to use centroid size as a proxy to analyze size, but we found our data does not provide accurate size references. Therefore, we focus on body diameter because it is the most available metric measurement for the ceramics we examined. We presented the result in the "Results" section and discussed it in the "Discussion" section as well (pp 12-14).

Given that those morphological differences revealed by the authors are temporal, I find myself curious whether they have considered phenotypic trajectory analysis to characterize shape change through time? That would potentially bolster this analysis, and provide the evidence needed for a shift away from discussions of shape differences, and toward more complex discussions of shape change (Collyer and Adams 2007, 2013).

>>> We agree with Dr. Selden's perspective that phenotypic trajectory analysis has the potential for discussing shape changes in a sophisticated way. But we think it would work better for more diverse or complex shapes, which is not a case for our samples. Our samples have subtle differences, that is one reason we used the EFA-based GMM to capture the changes in overall shapes. We believe the methods we have used (plus shape analysis and morphological disparity that we added based on the reviewer's comments) could provide sufficient results for our discussion on ceramic standardization and craft specialization. The study of shape change is an interesting topic, but it is a little out of the scope of this paper. With the word limits in mind, we would like to focus on our main topic of standardization and ceramic specialization. However, we appreciate this suggestion and we hope to use it for future projects on different archaeological assemblages.

This work is a valuable contribution to the field, and I believe—with some minor modifications—it will have a lasting impact on studies of ceramic morphology. Prior to submitting the revised manuscript, I would recommend that the authors review the most used/relevant keywords in/across the GM field, and critically assess how those may impact how their work may be compartmentalized in the future - https://aksel-blaise.github.io/gmbib/bibliometric-analysis.html. This is something that I am currently working through with colleagues, and believe that it holds value and utility in how our GM work(s) are discovered and used by like-minded analysts.

I look forward to seeing this in print.

>>> We thank Dr Seldon for the online source and we found that it is a really interesting study on the field of Geometric morphometrics. We have reviewed the most used keywords in the field by reading through their research. We have incorporated those keywords and assessed our work in the "Conclusion" section (pp.19).

Reviewer 1's comments directly on our manuscript:

>>> We really appreciate Dr. Selden's careful reading of our paper and taking time on editing. That is really helpful for improving our manuscript. We have accepted most of the edits, but some word choices remain unchanged since we found the original terms are more suitable to communicate our thoughts. Here we list our response to the significant comments that did not also appear in the main review text:

pp. 10 the comment: "Model these, and include the start/end probability distributions in your paper or supplemental data. I would recommend using the oxcAAR package, which would give you a way to incorporate that into your analysis script/materials. See an example in this article, and in the supplemental data - https://doi.org/10.1080/0734578X.2020.1744416. Illustrating the date ranges of the occupations is an important component."

>>> We added modelling of the radiocarbon dates using the oxcAAR package. We summarized our result in the background section about chronology (pp. 6) and included the script in our paper compendium here: https://doi.org/10.17605/OSF.IO/ABVGF. We would like to clarify that our decision of three phases is mainly based on chronologically diagnostic artifacts since the few radiocarbon ages available tend to have long time ranges that are not suitable to assign historical phases with short time ranges. However, we found the model is useful to present and visualize chronology and we added it as supplementary data.

pp. 11 Was this tested using statistics? If so, then state that there are no significant changes in the inclusions over time, and include that script in your supplementary materials.

>>> We have included the analysis of petrographic results in our paper compendium https://doi.org/10.17605/OSF.IO/ABVGF and provided the p-value in the main text to indicate there are no significant changes over time.

pp. 20 Not necessarily. I encourage you to consider the work of Kubler related to this point; his discussion of signals in particular –

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@book{RN20715,
author = {Kubler, George},
title = {The Shape of Time: Remarks on the History of Things},
publisher = {Yale University Press},
address = {New Haven},
ISBN = {9780300100617},
year = {1962},
type = {Book}
}
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>>> We have reviewed Kubler's discussion of signals, which is helpful to think about the transmission of style. We have a short sentence to incorporate this point in our discussion as well.

Reviewer 2

Reviewer #2: In "Investigating Shape Standardization using Geometric Morphometry of Pottery from Iron Age Northeastern Taiwan," the authors use geometric morphometric outline analysis to document variation in the morphology of cooking vessels from a cluster of sites before European contact (n=32 vessels), during colonization by Spanish and Dutch groups (n=27 vessels), and then under Chinese domination (n=14 vessels). The authors find that the variation decreases after European contact and again after the subsequent dominance by main-land China groups (i.e., variation in shape morphology decreases through time). According to the authors, the vessels become more oval-shaped though time (Lines 299 and 300). The authors ultimately conclude that this decrease in variation DOES NOT reflect changes in vessel use or paste composition, but instead reflects an emphasis on local social identity reflected in the use of distinctive, standardized pottery.

Overall, I find the paper worthwhile. It uses a straightforward method effectively and derives interesting results. I really only have two meaningful comments/suggestions. First, I would appreciate a more extensive consideration of the possibility that sample size in some way affects the analysis. The decreased variation correlates with smaller sample sizes. The use of the Coefficient of Variation should control for this as the authors note in a single sentence in line 203. However, a slightly more extensive discussion in the discussion section would be more persuasive. More specifically, I could easily imagine a reader wondering if a sample of 14 vessels might have less variation than a sample of 32 vessels simply because a smaller sample size is less likely to reflect unusual or less common vessel morphologies. To be clear, I do not think the results the authors report are the result of sample size. The difference between the 32 pre-contact vessels and the 27 European-contact vessels is too small to account for the apparently substantial decline in vessel morphology variation reflected in Table 1. The manuscript will be stronger if they address this topic directly. (As a side note, I would have loved to actually see the CVs for the three periods in addition to the MANOVA results.)

>>> We appreciate the reviewer's suggestions about the sample size. We recognize the small sample size of ceramics in the Chinese period and have expanded our discussion section to acknowledge this. We have discussed the possibility of a more standardized shape for smaller sample size, and clarified that it should not be a problem based on the use of the coefficient of variation (CV), and statistical test on the equality of CV (pp. 14). We removed the account of a substantial decline in variation in vessel shape between pre- and post-European contact. We have also clarified that there are differences in the average shape between pre- and post- European when examining MANOVA, but there is *no difference* in the degree of standardization with the CV test on the shape variables from those two periods. In other words, MANOVA is to test any significant difference between shapes across three phases, and the CV test (modified signed-likelihood ratio) is to test whether the CV values of shape variables differ significantly between phases. We also added CV values for the three periods in Figure 5, accompanied with descriptions about the changes in CV value over time in the "Results" section (pp. 12).

A more meaningful concern in my opinion is that the authors' explanation for the increased standardization seems very ad hoc and is not strongly argued. The authors contend that the decrease in variation reflects "choice" based on the apparent use of the pottery as an emblemic mark of ethnic identity (my wording, not theirs). This argument is based on common sense as an explanation that fits the pattern, but without strong theoretical or empirical support based on the information given in the background and analyses sections. It is perhaps correct, but Costin (2001) and many of the other authors they cite tend to hold that increased standardization at heart typically reflects a decrease in the number of artisans making a given quantity of vessels. The authors do evaluate whether the recovered pottery came from a more randomly dispersed locations or more non-random clusters. This does not address the fundamental issue of the number of producers. Given that the more typical explanation for increased standardization is not meaningfully evaluated, I am not certain their argument that the pottery became a source of ethnic identification/pride is correct. A more detailed argument is needed to convince me. This is not a fatal flaw in the paper, in that the results are still interesting. However, I feel that their 'conclusion' is more of a guess or hypothesis regarding what might have happened as opposed to a convincing argument of what did happen. I think their argument can be improved with minimal effort.

>>> We thank the reviewer for this thoughtful comment. We found it very helpful to improve our discussion. We have expanded the discussion (pp. 14-15) to address the number of producers based on Costin's (2001) definition. We have estimated the potential number of producers according to the information of the population at Kiwulan. We have also evaluated the possibility of the decline in population that may lead to high standardized shape in the Chinese period. For the ethnic identity, we have clarified that it is merely our speculation after examining all the possible factors that may have been one possible factor that contributed to shape standardization and have made it explicit in our text (pp. 18-19). We argue that it is a scenario that could happen in the colonial period based on some previous studies of the interactions between the Europeans and local indigenous people in other parts of the world.

Highlights:

- Iron Age pottery shapes from Kiwulan, Taiwan, were analyzed using elliptical Fourier analysis
- Statistical tests for the equality of coefficients of variation of shape coefficients were applied
- Significant differences in pottery shape were identified between culture contact phases
- Pottery shapes show high standardization after contact with mainland Han Chinese groups

Standardization of ceramic shape: A case study from the Iron Age pottery from northeastern Taiwan

Li-Ying Wang

Ben Marwick

22 August, 2020

The emergence of ceramic specialization in prehistoric societies is often linked to shifts in the complexity of social structures, because standardized ceramic production can reflect craft specialization and the presence of elite control. Previous work on identifying specialization relies on typological or linear metric analysis. Here we demonstrate how to investigate ceramic standardization by analyzing outlines of ceramic vessels. Outline analysis is useful because, unlike more commonly-used landmark analysis methods, it can effectively quantify shape differences for objects that lack distinctive measurement points needed for landmark analysis. We demonstrate this method using pottery from Kiwulan, a large multi-component Iron Age site (AD 1350-1850) in northeastern Taiwan. To measure ceramic specialization, we quantified pottery standardization by analyzing shape variables with reproducible geometric morphometric methods. We computed coefficients of variation (CVs) for shape coefficients obtained by elliptical Fourier analysis to test for shape standardization. We found significant differences in pottery shape and shape standardization that indicate changes in pottery production resulting from contact with mainland Han Chinese groups in northeastern Taiwan. Our case study, which includes an openly available research compendium of R code, represents an innovative application of outline-based methods in geometric morphometry to answer the anthropological questions of craft specialization.

Introduction

A major historical factor of social change in small-scale societies is often linked to the introduction of foreign or exotic trade goods to local Indigenous societies (Mullins, 2011). Monopolization of long-distance trade goods has caused substantial transformations in Indigenous economic, cultural, and socio-political systems (Dietler, 2005, 1997; Junker, 1993; Silliman, 2005). Pericolonial archaeology is the study of these indirect effects of colonialism, investigating areas where direct European colonial rule was limited, their conquests were often short-lived and unsuccessful, but commercial activities yielded economic and political impacts on Indigenous peoples living on the periphery of colonial control (Acabado, 2017; Trabert, 2017). Pericolonial situations were common during the 17th to 19th centuries in East and Southeast Asia where European trading activity was extensive, but direct European rule less widespread. An emerging priority in archaeological research in Asia is identifying the indirect influences that are apparent on Indigenous communities during the colonial period. For example, Acabado (2017)'s study of Ifugao society in the Philippines highland suggests economic and political intensification during the Spanish presence in the lowlands as a strategy of Indigenous peoples to resist Spanish conquests.

Indigenous societies' responses to colonial contact ranges from passive acceptance to active negotiation with the colonists, and accommodation or resistance of foreign intrusion

(Torrence and A. Clarke, 2000a). The responses can be identified through their daily cultural practices, such as their consumption patterns of foreign goods (Dietler, 2015; Given, 2004; Mullins, 2011; Scaramelli and Scaramelli, 2005; Silliman, 2001). In this paper we investigate the archaeology of a pericolonial situation at Kiwulan (ca. AD 1350-1850) (Chen, 2007), a large multi-component archaeological site in Yilan County, northeastern Taiwan, to identify the indirect impacts of colonial settler activity on local Indigenous societies. Yilan is an ideal context to study peripheral colonial influences because the Indigenous communities were isolated by geographical barriers, limiting the frequency of direct contact with the Spanish and the Dutch settlers in northern Taiwan (cf. Berrocal et al., 2020). Kiwulan is situated on a hill near a riverside at the northern margin of Yilan County, which is characterized by a triangular alluvial plain facing east toward the Pacific with high mountains on three other sides.

This research investigates if there was increasing ceramic specialization resulting from Indigenous interaction with Europeans in the 17th century, or Chinese in the 19th century. These were the two major foreign influences in early historical Taiwan that may relate to social changes in Indigenous societies. We predict that competition within the Indigenous community at Kiwulan for foreign resources and trade partnerships with European or Chinese colonizers may have led to the emergence of craft specialization, caused by greater economic and social control of ceramic production by a small group of individuals. Using standardization in ceramic shapes as a proxy for craft specialization, we ask: Did colonial trade impact the shape of locally-produced Indigenous pottery vessels? Did pottery shape become more homogeneous after foreign contacts with European colonizers or Chinese immigrants?

Several measurements have been used for investigating ceramic standardization that include metric, compositional, and technological variables (Arnold, 2000; Blackman et al., 1993; Boness et al., 2015; Costin, 1991; Rice, 1991; Roux, 2015; Tite, 1999). Among those variables, metric measurements are most widely applied to archaeological assemblages. The coefficient of variation (CV) statistic is regularly used to quantify the degree of standardization in ceramic assemblages (Eerkens and Bettinger, 2001; Junker, 1999; Roux, 2003; Stark, 1995). However, because pottery vessels typically have curved shapes, linear measurements have limited sensitivity to many kinds of shape variations. Thus, to capture subtle shape variations that might also be relevant to standardization, we analyze ceramic shapes using geometric morphometric methods (GMM).

Geometric Morphometrics

Geometric morphometrics (GMM) differs from traditional linear measurements through its use of Cartesian coordinates of morphological structures to quantify and analyze shape (Adams et al., 2004; Bookstein, 1997; Lawing and Polly, 2010; Slice, 2007). Landmarks, curves or outlines of objects can be represented by coordinates in terms of their unique point locations with respect to numerical values on coordinate axes. There are two common morphometric approaches: landmark and outline methods (Adams et al., 2004). Landmark GMM approaches assign a set of landmarks and/or semilandmarks onto objects as reference points. Generalized Procrustes analysis (GPA) is used to superimpose landmark data on a common coordinate system by translating, rotating, and scaling

(Bookstein, 1991). After the GPA procedure, superimposed landmark coordinates become shape variables that allow further statistical analyses (Slice, 2007). A common procedure is using dimensional reduction techniques, such as Principal Components Analysis or Canonical Variate Analysis, to capture the key features that represent the overall shape. Visualization of the reduced data enables the identification of groups, followed by statistical tests to robustly distinguish them. Landmark-based morphometrics have been widely applied to archaeological objects with obvious morphological features that provide unambiguous reference points for landmark placement, such as tips and edges of stone or metal tools (Birch and Martinón-Torres, 2019; Lycett and Cramon-Taubadel, 2013), visually distinctive bone features (Haruda et al., 2019; Meloro et al., 2015), or ceramic assemblages with distinct components (Selden Jr, 2019; Topi et al., 2017). This approach is often used to answer research questions related to lithic typological and technological change (Doyon, 2019; Eren et al., 2015; Perez, 2007; Presnyakova et al., 2018; Selden et al., 2018), animal domestication or mobility (Haruda et al., 2019; Owen et al., 2014), or hominid activities through cutmarks and taphonomic traces (Aramendi et al., 2019; Courtenay et al., 2019).

Key questions in archaeological shape analysis normally involve measuring shape standardization over time, or between geographical areas. Standardization is often investigated using multivariate analysis of shape variables computed from landmark data, along with coefficients of variation on associated metric data, especially for lithic assemblages. For example, Archer et al. (2015)'s case study of stone points in Southern Africa suggests an increase in shape standardization over time that may relate to increased maintenance of finished points. Buchanan et al. (2018) analyzed lithic morphology with metric data and identified a more uniform base-shape of Folsom points compared to Clovis points across the western US. With similar methods, Smith and DeWitt (2016) found standardized bases of fluted points in Alaska and northern Yukon that might indicate a risk management strategy to ensure the ease of replacement during long-distance travel. Other factors, such as low levels of cultural innovation in a small group, could also lead to an increase in standardization of point shapes (Okumura and Araujo, 2014). To test the effectiveness of measuring standardization, Birch and Martinón-Torres (2019) compared landmark-based GMM to traditional metric analysis with CVs using European iron weapons as an example. They demonstrated that landmark-based GMM can capture more variation in not only overall shape, but also bilateral symmetry.

For ceramics, Topi et al. (2017) identified that two types of the Casas Grandes vessels in northwest Mexico tend to have standardized shapes, using coefficients of variation for the positions of semi-landmarks across shape groups. They suggested standardization might hint at the presence of specialized producers, reflecting social complexity. Another way to explore standardization is pairwise testing of variations in morphological disparity between shape groups by calculating their distances in morphospace, an n-dimensional space that shape groups occupy (Wills, 2001). In this manner, Seldon (2019, 2018) examined Caddo ceramics in northeast Texas using semi-landmark approaches and found an increase in shape standardization over time, providing a basis for further discussion of craft specialization or group identity. Similarly, the Gahagan bifaces from the central Texas exhibit less size standardization than those from the southern Caddo area, indicating different uses or tool types (Selden Jr et al., 2020). Other applications, such as studies of cranial deformation, demonstrate that landmark approaches with multivariate analyses of shape variances are useful to evaluate shape standardization (Kuzminsky et al., 2016; Natahi et al., 2019; Perez, 2007).

A key limitation of landmark approaches in archaeology is that landmarks may be difficult to reproducibly locate for structures that are mostly or entirely curves, if not mathematically-defined. In those cases, outline approaches, such as Elliptic Fourier Analysis (EFA), are more effective for assessing morphological variations in the whole structure of two-dimensional closed shapes (Cardillo, 2010). EFA uses periodic functions to capture geometric information, where an outline is decomposed into a series of ellipses described by trigonometric functions (Adams et al., 2004; Bonhomme et al., 2014; Claude, 2008). That is, coordinates along a curve are converted into Fourier function coefficients, called harmonic coefficients or harmonics (Kuhl and Giardina, 1982). The number of harmonics determines the quality and precision of the geometric representation of an object. The harmonic power, a cumulative sum of squared harmonic coefficients, provides a robust rule for determining the desired number of harmonics (Bonhomme et al., 2014). The first systematic use of Fourier series to analyze shapes of artifacts in archaeology was Gero and Mazzullo (1984)'s study of lithic flakes in Peru. They successfully identified the changes in tool shape from a more angular to rounded shape over time. Later, Saragusti et al. (2005) introduced more functions allowing the calculation of the specific shape attributes, such as symmetry, roughness, and deformation. This demonstrated the potential of EFA for the analysis of curves in detail. Ioviță (2009) demonstrated a protocol, including outline digitization, EFA procedure, and multivariate linear regression, to compare resharpening trajectories of European Middle Paleolithic stone tools. He found that resharpening can be independent of morphology, suggesting that functional attributes should be studied separately. Recent case studies further support the effectiveness of EFA for examining lithic assemblages, e.g. for typological classification of Late Woodland points (Fox, 2015), analysis of the function of flaked obsidian tools in Easter Island (Lipo et al., 2016), study of the shape and symmetry standardization of the British Acheulean (Hoggard et al., 2019), and investigating cultural taxonomies of the European Late Palaeolithic (Ivanovaitė et al., 2020).

Despite few ceramic studies using EFA to date, this approach is promising for analyzing ceramic taxonomy and standardization. For example, Wilczek et al. (2014) evaluated the concordance between EFA and Discrete Cosine Transform (DCT), and a traditional typology by studying 154 complete ceramic vessels with varied shapes from the Bibracte oppidum in France. They found that the variation indicated by EFA and DCT matches the traditional ceramic typology, which supports the claim that outline-based approaches can be efficiently used for studying variations in ceramic shapes. Wilczek et al. (2014)'s findings demonstrate the potential of EFA for detecting variation in ceramic standardization. In this paper we use EFA to evaluate the level of standardization of ceramics data from Kiwulan, northeastern Taiwan around the time of foreign colonial presence to gain insight into the emergence of ceramic specialization. The globular shape of the vessels in our sample means that our specimens lacks visually distinctive landmarks, so EFA is an ideal method because of its focus on the overall shape of an artifact. In addition, we use a novel significance test for the equality of coefficients of variation of shape variables to statistically compare vessel standardization from different periods.

Archaeological background and materials

Ceramics analyzed in this study come from 40 units (4m by 4m each) sampled from the central, undisturbed area of archaeological excavations at Kiwulan (Figure 1; Figure 2). The chronology of the archaeological deposits consists of two cultural components, the upper and the lower, with a sterile layer in between (Chen, 2007). We focus on the upper component, dated from AD 1350 to 1850, because it spans the late Iron Age and the historical period. The historical period in Taiwan started with the presence of the Europeans in the early 17th century. The Dutch first occupied southern Taiwan in 1624, followed by the Spanish in northern Taiwan in 1626 (Andrade, 2007). In 1642, the Spanish were expelled by the Dutch, who then took over the Spanish forts at Helping Dau in Keelung, and in Tamsui. Western Taiwan remained under Dutch colonial rule until 1662 when the Kingdom of Tungning in Taiwan was founded by Koxinga, a loyalist of the Ming dynasty of China (Andrade, 2007).

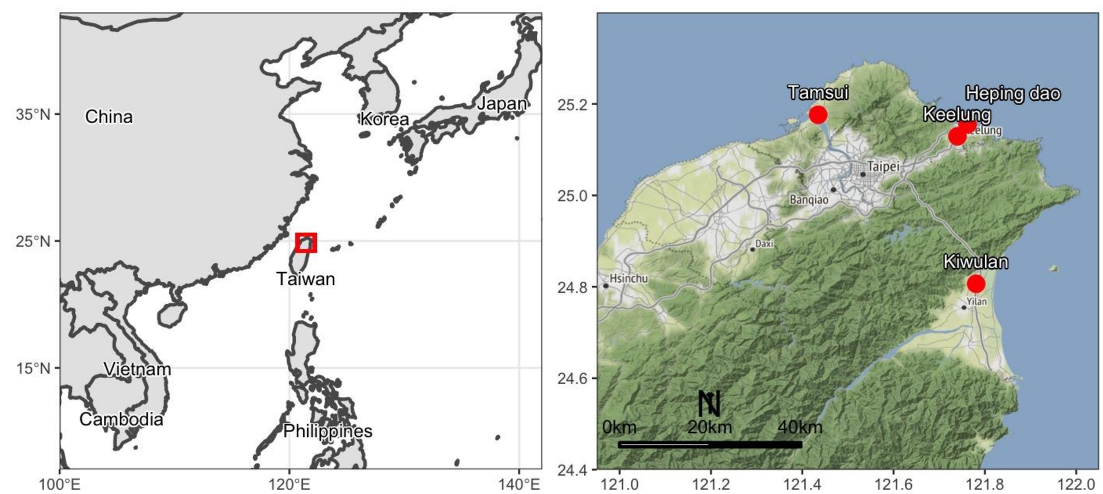


Figure 1: Map illustrating the location of Kiwulan, and other locations in northern Taiwan that are named in the text. Map data is from naturalearthdata.com

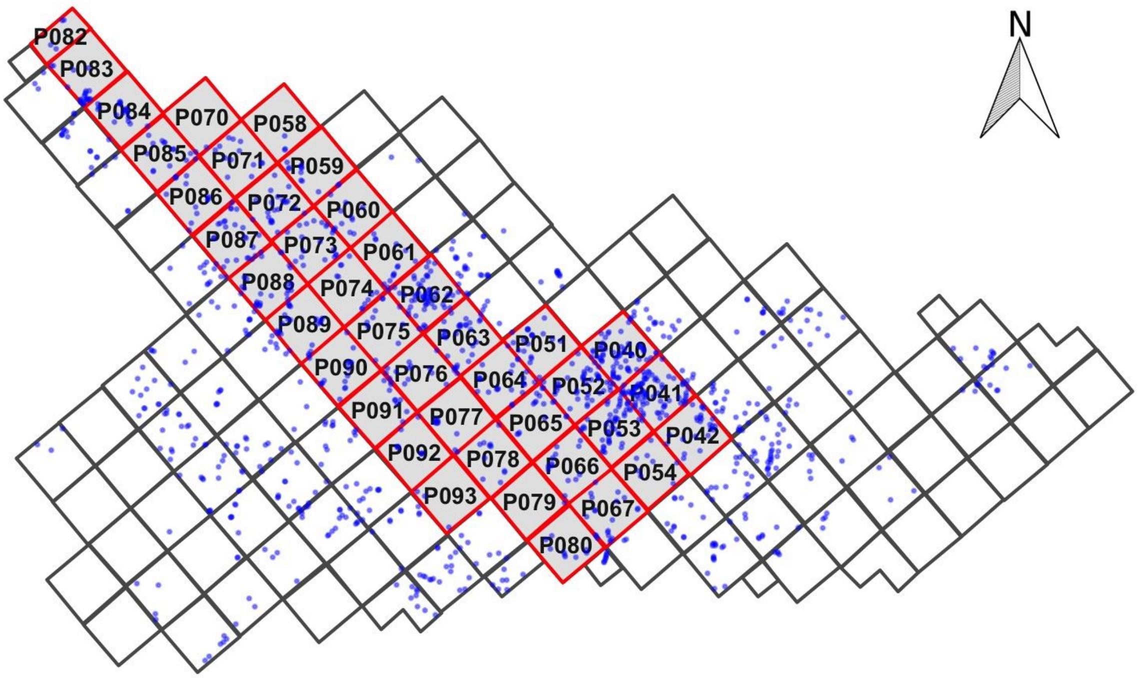


Figure 2: Map showing the largest section of excavation areas at Kiwulan, and the distribution of forty squares sampled in this paper presented in red with square ID number. Small dots represent the location of post-holes. Each square is 4 x 4 m

The archaeological record of Kiwulan's upper component shows traces of foreign contact, including Europeans in the 17th century, and waves of Chinese immigrants in the 19th century. Imported ceramics from mainland China, stoneware, and ornaments such as beads have been recovered in the upper component, indicating frequent long-distance trade activities with Europeans and Chinese merchants. Archaeological features such as burials, middens, and post-holes with *in-situ* posts are widespread across the 1-2 m thick deposit of the upper component, and demonstrate that Kiwulan was a continuously occupied large settlement site (Chen, 2007). To compare different foreign influences, we classified the upper component into three chronological phases: pre-European, European, and Chinese. These phases were identified according to chronologically diagnostic artifacts. Our Bayesian modeling of 11 ages related to the upper component from Chen (2007) shows a consistent result with our artifact-based chronology. However, because the three phases are relatively brief and the number of ages is small, radiocarbon modeling is of limited value to chronology building in this case (more details in Wang and Marwick, 2020). The diagnostic artifacts include blue and white porcelains, light grey glazed jars, and large dark brown glazed stoneware jars commonly used in the 17th century, and bricks and tiles employed by the Chinese in the 19th century (Chen, 2007; Hsieh, 2009; Wang, 2011). We also examined excavation depth measurements and stratigraphic details reported by the excavators (color, texture, disturbance, etc.) to reliably separate the three phases. The deposit exhibited signs of continuous human occupation in each of the three phases with no apparent breaks. More details for the assignment of different phases are in the Online Supplementary Materials (Wang and Marwick, 2020).

The most abundant artifacts in the upper component are locally manufactured ceramics, which are distributed throughout the temporal sequence, and across the study area. More than 550,000 sherds were recovered, and around 1,200 vessels could be completely or partially reconstructed (i.e. complete rim or base). There are two shapes of locally-manufactured vessels; a cooking pot and a steamer made of two cooking pots stacked together with a clay filter between. Those vessel shapes demonstrate suites of standard morphological components. Each has a globular body with a short neck and wide mouth (Figure 3). The exterior surface below the neck is decorated with a variety of impressed geometric motifs. These vessels were likely used for cooking, as indicated by the frequent presence of charred residues and carbon deposits on vessel interiors, and soot on vessel exteriors. Firing resulted in orange and brownish color with a fully oxidized core, or a reduced core with oxidized fringes (Chen, 2007). The vessels were believed to be made with pinching technique according to some hand-shaped traces on vessel interiors, such as finger impressions and seams. This kind of vessel has been widely found at archaeological sites during the late Iron Age and the historical period throughout the Yilan Plain (National Musuem of Taiwan History, 2005).

Petrographic analysis for 34 thin sections presents a high percentage of inclusions (15-50%), including argillite (15-40%), metasandstone (1-10%), sandstone fragments (1-6%), quartz (1-5%), and trace amounts of feldspar and slate. Particle sizes range from 500 to 1300 microns. In general, the vessel fabric presents a mixture of fine, rounded argillite with a small amount of rounded metasandstone and rounded sub-angular monocrystalline quartz. This composition is consistent with the mineralogical composition of local raw materials found in the Yilan Plain (Chen, 2016). There are no significant changes in the inclusions over time, indicating continuity in pottery fabric composition across the three periods ($p = 0.7159$) (Wang and Marwick, 2020).

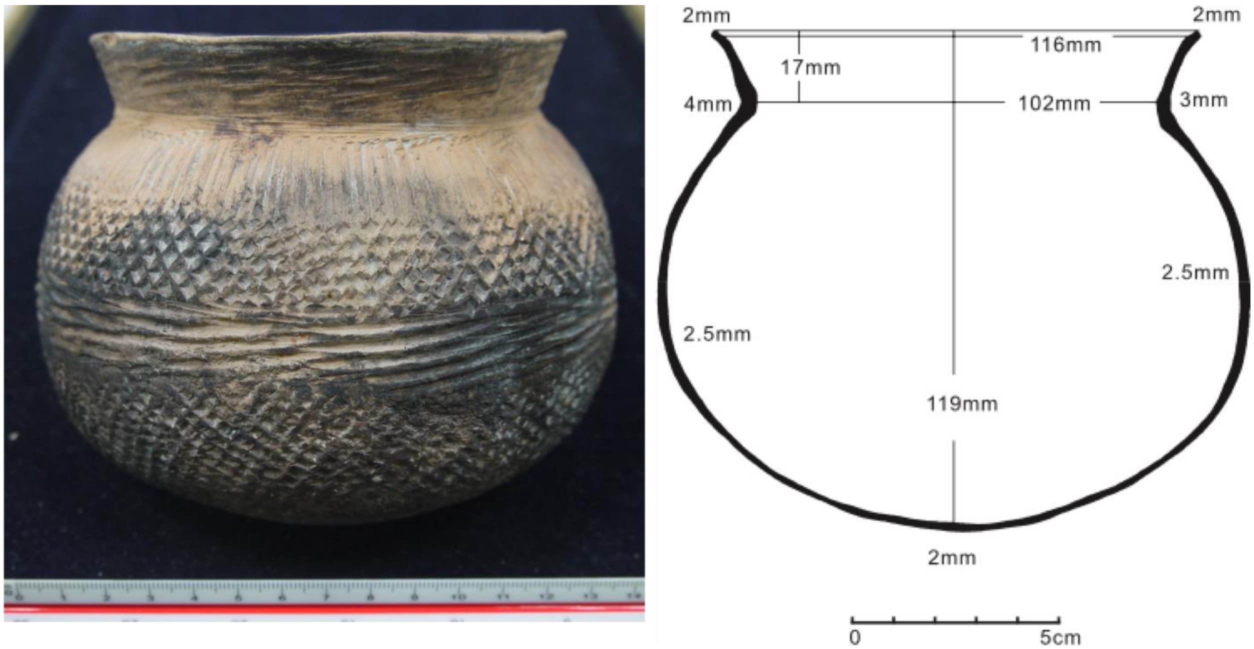


Figure 3: A typical pot from Kiwulan (left) and an example of a pottery drawing used for outline analysis (right)

Methods

The sample consists of 73 reconstructed vessels with rim, body and base parts that were securely provenanced to pre-contact (n = 32), post-European (n = 27), and Chinese contact contexts (n = 14).

Digitizing and analyzing by EFA

We used 300 dpi scans of pottery drawings acquired from the Bureau of Cultural Affairs in Yilan (Figure 3). All drawings provide a two-dimensional view of vessel cross-sections based on metric measurements. The scanned drawings were imported into Inkscape (http://inkscape.org) for digitization where outlines were manually traced. In those instances where only one side of the cross-section image was available, or small sections were missing, we interpolated the curves and then mirrored and joined to create a closed outline for each vessel. Analyses were conducted using R software (R Core Team, 2019) with functions from the Momocs package for quantifying and analyzing shapes (Bonhomme et al., 2014). Outlines were converted into a list of successive x and y pixel coordinates for EFA. We analyzed harmonic coefficients by principal component analysis (PCA) for dimensionality reduction to illustrate the diversity of the shape data and identify major patterns of variation.

Statistical analysis

The principal component (PC) scores were analyzed with a multivariate analysis of variance (MANOVA) to test significant differences in shapes between occupation phases.

We also computed coefficients of variation values (CVs) for the PCs, treating the PCs as shape variables that are more informative than linear dimensions. The coefficient of variation is a common and widely-used statistical measure of the spread of a set of measurements of a sample. It is defined as the standard deviation divided by the mean:

$$c_v = \frac{\sigma}{\mu}$$

As a standardized measure of the spread of data, coefficients of variation (CV) allows a direct comparison for variation in samples measured with different units or means. This is useful to examine the degree of standardization for archaeological assemblages and enables comparison of variation across different sample sizes (Eerkens and Bettinger, 2001, p. 498). Following Eerkens and Bettinger (2001) and Roux (2003), we take this as our measurement of standardization in vessel shape variables: lower CV values reflect higher standardization, and thus increased craft specialization in the community. Given that CVs are most informative when computed on either all positive values or all negative values, we normalized PC scores to a range between 1 and 10 for the computation of CV.

To answer the question of whether CV values across our three occupational phases are significantly different or not, we used the modified signed-likelihood ratio (MSLR) test for equality of CVs (Krishnamoorthy and Lee, 2014). While previous work has used the Feltz and Miller (1996)'s asymptotic test for the equality of coefficients of variation from k populations (Eerkens, 2000; Eerkens and Bettinger, 2001; Hoggard, 2017; Lycett and Gowlett, 2008; Okumura and Araujo, 2014), we prefer the MSLR test for shape variables as a more recent development with lower rates of type I error, better performance with uneven sample numbers, and more power across a range of conditions (Krishnamoorthy and Lee, 2014).

To complement our investigation of craft specialization through shape standardization, we investigated spatial patterns of ceramic vessels at Kiwulan. As craft specialization increases, we expect a shift from a pattern of vessels dispersed across the site to a pattern of clusters that reflects the loci of production (Costin, 2001). We used a Monte Carlo test for randomness in spatial locations of ceramics to robustly test whether their distribution is significantly clustered or dispersed.

Reproducibility and open source materials

To enable re-use of materials and improve reproducibility and transparency (Marwick, 2017), the entire R code (R Core Team, 2019) used for all the analysis and visualizations contained in this paper is openly available online at https://doi.org/10.17605/OSF.IO/ABVGF (Wang and Marwick, 2020). Also in this version-controlled compendium (Marwick et al., 2018) are the raw data for all the visualizations and tests reported here. All of the figures, tables, and statistical test results presented here can be independently reproduced with the code and data in this repository. The code is released under the MIT license, the data as CC-0, and figures as CC-BY, to enable maximum re-use.

Results

Thirteen harmonics captured 99% of the total harmonic power in the elliptic Fourier coefficients of 73 vessels from three phases. Figure 4 illustrates differences in vessel shapes using thin-plate spline warping for paired periods, pre- and post-European periods, and post-European and Chinese periods, with the greatest differences evidenced between pre-European and Chinese periods.

The first two principal components (PCs) of the PCA on the elliptic Fourier coefficients explain 74.85% of the total variance, of which 48.32% is explained by the first principal component. With the third component, the first three principal components explain 86.08% of the total variance. PC1 captures the height of the vessels, from tall to short, and the roundness of the body from round to oval-shaped (Figure 4). PC2 relates to the neck and mouth constriction, from narrow to wide. PC3 explains a smaller portion of the variance (11.23%), which relates to the degree of the flare in the neck, from a curved to a straight shape. The results reflect a large overlap in shapes from three occupations phases, especially for shapes in the pre-European and post-European periods. However, the spread of shape distribution indicates a wider variation in shapes in the pre-European and post-European periods compared to those in the Chinese period along both PC1 and PC2 axes. In other words, we find a decrease in shape variance in the Chinese period evidenced in the shorter height and narrower mouth of vessels used in that period.

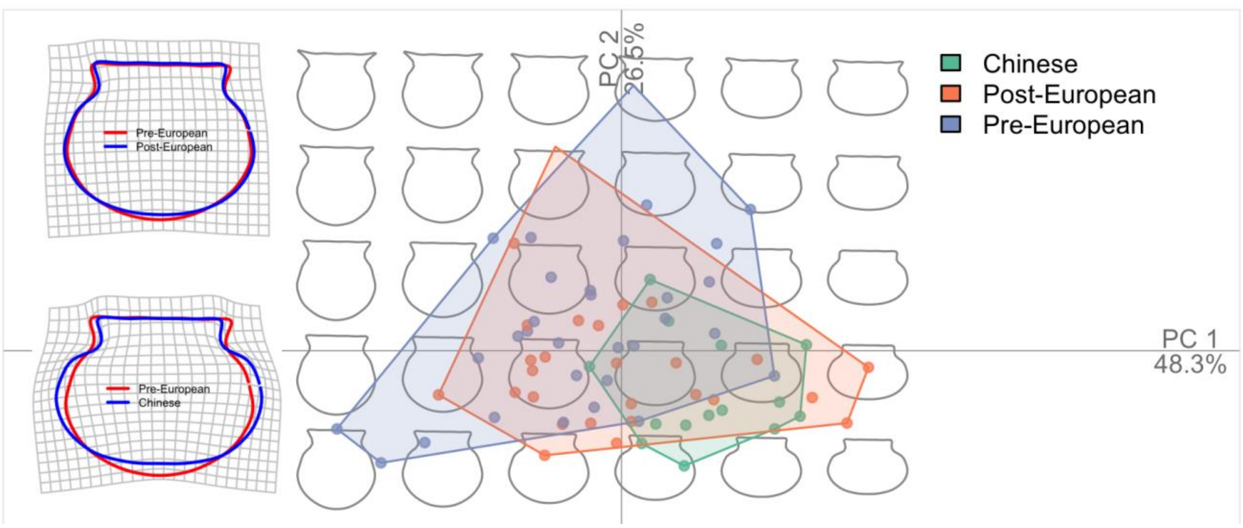


Figure 4: Left: Significant differences in average vessel shapes between the Chinese and the post-European period are visible using thin plate splines (TPS), with outline deformations required to pass from an extreme of one morphospace to another. Right: Pottery shape distribution by each occupation phase according to the first two PCs.

Table 1: Summary statistics for the MANOVA test on the PC scores. `Pr(>F)` *is the p-value associated with the F statistic of the effect and test statistic.*

Comparison	Pillai's trace	Approximate F value	degrees of freedom	Pr(>F)

Chinese - Post-European	0.3806	1.6202	29	0.1452
Chinese - Pre-European	0.6942	7.0177	34	0.0000
Post-European - Pre-European	0.3491	2.2917	47	0.0243

To test for differences in the distributions of shape variables indicated by the PC scores shown in Figure 4, we used a multivariate analysis of variance (MANOVA) test to compare pairwise combinations across the three occupation phases. Table 1 demonstrates the significant differences in shape between Pre-European and Post-European phases ($p = 0.0243$), and Pre-European and Chinese phases ($p = 0$). These results are consistent with the differences in the visualization of average shapes between the phases (Figure 4, see left). Although there is considerable overlap of shape variables between the Pre-European and Post-European phases, their PC scores differ significantly. There is no significant difference in vessel shapes between the Post-European and Chinese contact periods.

To compare pottery shape standardization across the three phases we investigated the distributions of the first three PC scores, taking the PC scores as proxy variables for vessel shape (Figure 5). The CVs calculated of the three PC support a general trend toward a more standardized shape over time, especially the shape identified by PC1 that represents vessel height and roundness. PC1 shows a higher variation in the pre-European period and post-European period compared to the Chinese period. That is, a more standardized shape found in the Chinese period. However, PC2 presents a similar diversity in ceramics assemblages across three phases, while PC3 demonstrates a slightly standardized shape in the Chinese period.

To see whether the differences in the distribution of PCs between any two phases are substantive or due to chance, we assessed the equality of CVs for PC1 and PC2 with a modified signed-likelihood ratio test (Krishnamoorthy and Lee, 2014; Marwick and Krishnamoorthy, 2019). P-values for PC1 show significant differences in shape standardization across periods, between Chinese contact with either pre-European or post-European (Table 2). This result supports the observation of a more highly standardized shape in the Chinese period.

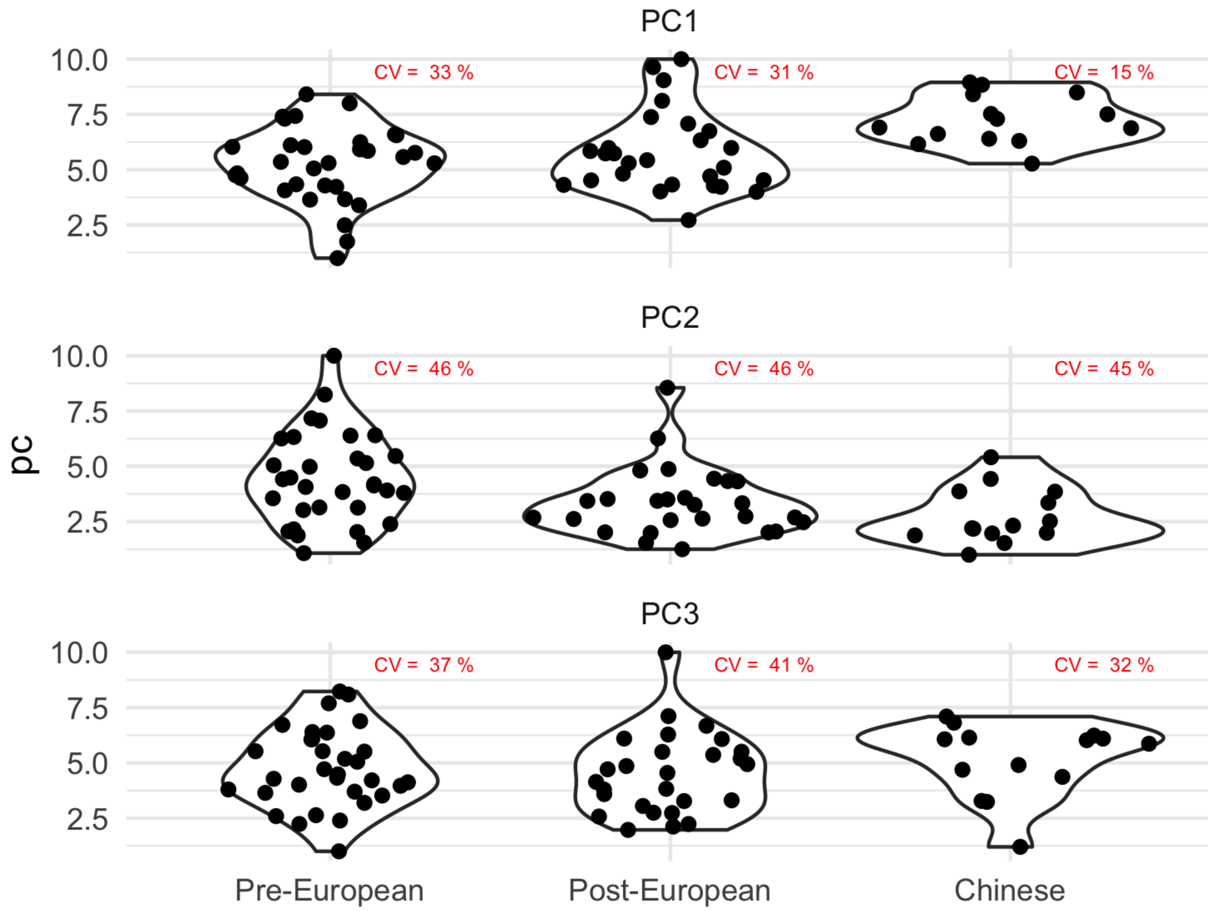


Figure 5: The distribution of normalized PC scores by phases. CV values (%) are shown in the upper right of each plot.

Table 2: P-values of the CV equality test of PC1 and PC2 between phases

PC	MSLRT	p-value	phases
PC1	0.0569	0.8115	Post-European vs Pre-European
PC1	8.2930	0.0040	Chinese Contact vs Pre-European
PC1	6.4299	0.0112	Chinese Contact vs Post-European
PC2	-0.0520	1.0000	Post-European vs Pre-European
PC2	0.0844	0.7714	Chinese Contact vs Pre-European
PC2	-0.0104	1.0000	Chinese Contact vs Post-European

Vessel size is another important variable for detecting standardization. We used the body diameter of vessels as a proxy of size to examine their variation and relationships with vessel shape. We measured body diameter directly from each physical vessel in the collection, and we focus on this metric because it is available for more vessels than any other metric. The body diameter of vessels from the Chinese period is larger than those from the two earlier periods, and vessels from before European contact have the smallest body diameter on average (Figure 6: A). To investigate vessel form standardization, represented by shape and size, we compared CV for PC1 (as a shape variable) in relation to CV for body diameter (as a size variable). The result (Figure 6: B) shows a higher standardization in vessel form in the Chinese period, with smaller CV values compared to those from the other two phases. However, there are no obvious differences in form standardization before and after the European presence. To understand the relationship between shape and size, we computed linear regression models for PCs and body diameter (Figure 6: C). The results demonstrate that shape and size are positively correlated in all phases, as indicated by moderate positive relationships (0.3 ≤ r ≤ 0.7) and small p-values (≤ 0.05), except for PC1 in the Chinese period and PC2 in the pre-European period. In general, the shorter vessels are larger in body diameter according to the significant positive correlation. However, vessels from the Chinese period do not show this pattern. For the relationship between PC2 and body diameter, the negative relationship suggests that vessels with a narrower neck and mouth tend to have a larger body diameter.

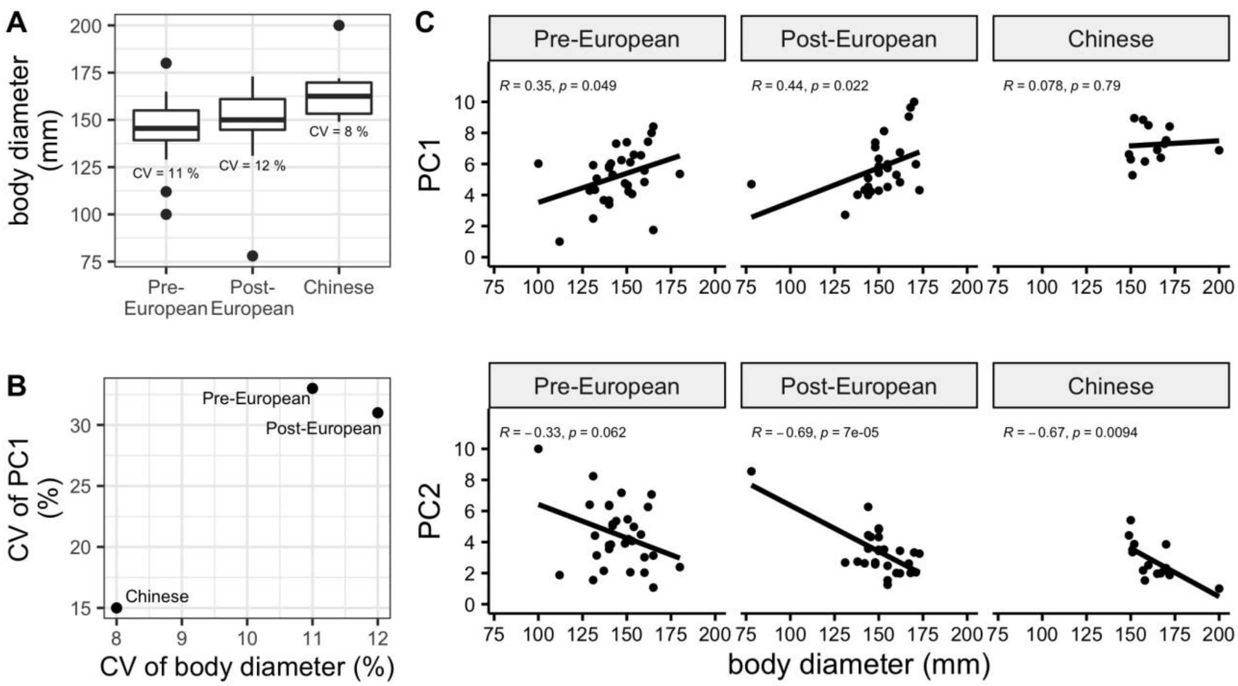


Figure 6: A: Distribution of the body diameter of vessels with coefficients of variation by phases. B: Coefficients of variation of vessel shape represented by PC1 in relation to vessel size represented by body diameter, showing more standardization (lower CV values) in vessel form and size in the Chinese period. C: Correlation between shape variables (PC1 and PC2) and body diameter of vessels with Pearson's r and p-values by phases

Discussion

Previous investigations at Kiwulan suggested an unequal distribution of prestige goods with high diversity in types, trade ornaments in particular, following the appearance of

Europeans (Cheng, 2008; Wang, 2011). This hinted at the emergence of social inequality within the Indigenous community. To investigate this possible relationship between social inequality and foreign presence, we examined shape standardization of ceramics to measure craft specialization as a proxy for social change (Costin, 2001; Junker, 1999). The result of our MANOVA demonstrates significant differences in shapes between the pre-European and Post-European periods, and pre-European and Chinese periods. The average shape presents as a round body with a wide rim and neck before European contact, which shifts to a more oval-shaped body with narrower rim and neck after the European presence. Such shape is more pronounced in the Chinese period. In general, vessels become oval-shaped with a restricted mouth over time, which corresponds with an increase in body diameter of vessels. The correlation between shape and body diameter suggests that body diameter significantly varies with vessel shape. Oval-shaped vessels with a narrower opening tended to have a larger body diameter, indicative of a change in overall vessel form.

For the degree of shape standardization, our CV tests on PC1 indicate a significant difference between the Chinese period and either pre-European or post-European periods. Analysis of morphological disparity, which measures the positioning of specimens relative to one another in the morphospace (Hopkins and Gerber, 2017), supports our finds of shape differences between Chinese contact and either pre-European ($p = 7.159 \times 10^{-23}$) or post-European periods ($p= 2.065 \times 10^{-25}$) (Wang and Marwick, 2020), suggesting a more standardized shape after contact with the Chinese. In addition, we found a more homogeneous shape accompanied by a more standardized but also larger size in the Chinese period. Generally, people tend to make mistakes in hand-crafting as the size of an object increases, leading to higher variations in larger artifacts (Eerkens and Bettinger, 2001). However, we found the opposite for ceramics in the Chinese period when using body diameter as our proxy variable of size. This might hint an intentional behavior by Kiwulan potters to achieve a homogeneous form for the larger vessels. Mineral composition shows that the clay pastes are similar throughout three phases, regardless of the increasing standardization of the pottery shape, reflecting continuity in the raw material sources. We can thus rule out changes in clay fabric as a factor in explaining changes in vessel shape. We note that a small sample size in the Chinese period may lead to a more standardized shape. However, this effect can be reduced using CV statistics that scales variation to magnitude, allowing reliable comparison across uneven sample numbers, even for small sample size (Eerkens and Bettinger, 2001). Moreover, the MSLR test for equality of CVs enables a robust test between different sample numbers (Krishnamoorthy and Lee, 2014).

Whether the shape standardization we found results from craft specialization depends partly on the number of producers, which distinguishes mechanical standardization from intentional standardization defined by stylistic and functional attributes (Costin, 2001; Costin and Hagstrum, 1995). Mechanical standardization is related to the appearance of specialized production based on the assumption that increased skills, routinization, and lower diversity of producers will lead to morphological uniformity (Arnold, 2000). In our case, relative changes in the potential number of producers may be inferred from changes in population size at Kiwulan. According to the Dutch census in 1648 (Nakamura, 1938, p.

12), the population at Kiwulan was large but declined in the Chinese period due to the movement of Indigenous people to the south (Chen, 2007). This change in population corresponds to a decline in ceramic abundance at Kiwulan. Thus, we model CV values as a function of the mass of ceramics using Poisson GLM with a link function. The model suggests that ceramic abundance strongly predicts the CV values ($\beta = 0.06957$, $p = 0$). This indicates that the more standardized vessel shape of the Chinese period may be influenced by a small population, and thus smaller number of pottery producers, if ceramic abundance can be taken to reflect the population size.

However, intentional standardization due to considerations of function or style could also contribute to the shape standardization in our case. To explore this aspect of the relationship between shape standardization and craft specialization, we investigated the function and surface decoration of the vessels. We used geochemical methods to extract and identify lipids trapped in the fabric of potsherds to identify foods that may have contributed residues absorbed into the clay (cf. Kwak and Marwick, 2015). Unfortunately, we did not obtain useful results due to extremely low lipid yields, which were probably due to the very thin, dense, and low porosity fabric of Kiwulan pottery. These physical characteristics of the clay offer limited spaces to trap and protect organic molecules from microbiological degradation (cf. Evershed, 2008, p. 909). To analyse style, we defined surface impressed decorations, usually consisting of multiple bands of geometric motifs, as types of decorations. If two pots shared the same set of motifs but different arrangements of single bands, we considered them two different types. In general, the ceramics in the Chinese period have slightly fewer variations in decoration according to the ratio of distinct types to the total number of pottery from each phase (Chinese = 0.71, post-European = 0.81, pre-European = 0.78) (Wang and Marwick, 2020). The limited evidence about function, and slight differences in style suggest that intentional standardization may have played only a minor role at Kiwulan, and further evidence is required to completely rule out this factor.

Additional insight into craft specialization at Kiwulan comes from the spatial pattern of ceramics, which provides information about potential production units and production areas (Costin, 2001). Figure 7 shows that the pottery samples have a widespread distribution with high densities of pottery at some units during the European presence. Hypothesis testing on spatial randomness indicates a non-randomly dispersed distribution before European contact and a more extreme dispersed distribution after European presence. In contrast, the distribution of pottery is more similar to random distributions during the Chinese period. This is interesting because it contradicts our expectation that a clustered pattern will be observed with an increase in pottery standardization caused by the emergence of specialized groups (Costin and Hagstrum, 1995). The absence of clusters in the Chinese period is notable because this was a time of a historically-documented decline of the Indigenous population (Chen, 2007; Hsieh, 2009). We might expect reduced numbers of potters to result in pottery production shrinking to a few locations in the settlement during this time. However, despite the small number of vessels during the Chinese contact period, Figure 7 shows that pottery is distributed randomly across the sampling area without any distinctive clusters during this time. As population across our three occupation phases declines, we see less clustered distributions of pottery, supporting an interpretation of intentional standardization rather than mechanical standardization. The spatial pattern shows that ceramics were mostly household-produced, and no specific facilities of production are evident (Chen, 2007).

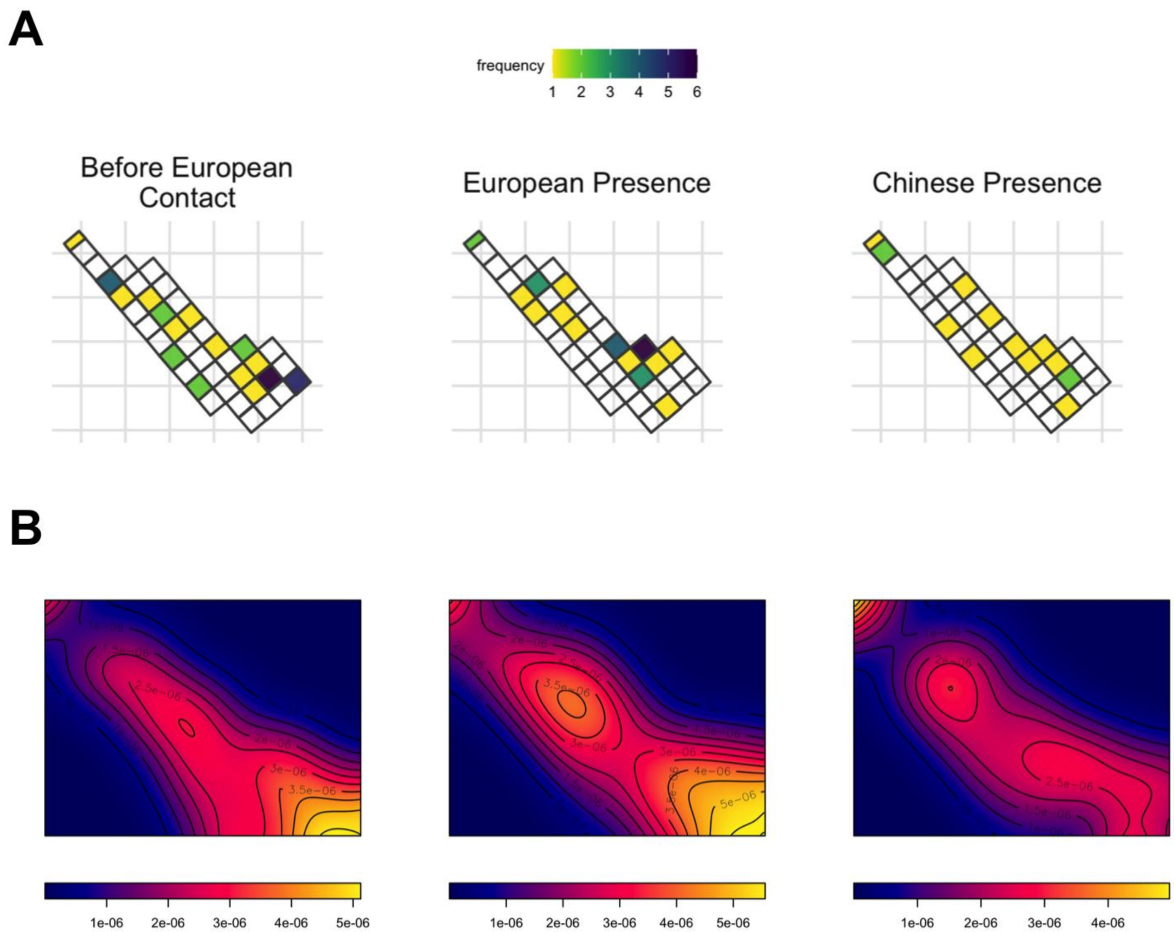
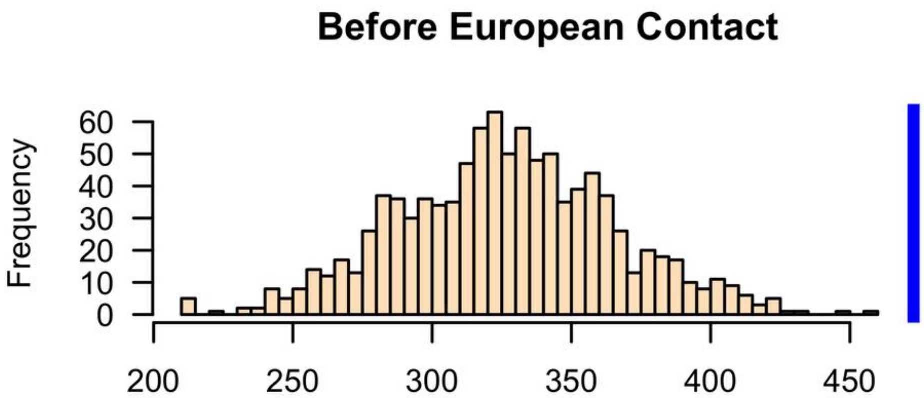


Figure 7: A: The spatial distribution of the pottery selected for shape analysis. The quantity is indicated by the color scale. B: Kernel density maps visulize the probability of the density of pottery across space. The maps show a major core area during the pre-European period, multiple core areas during the European period, and a single core during the Chinese period. The bandwidth is based on Silverman (1986)


Before European Contact
Frequency
0
10
20
30
40
50
60
200
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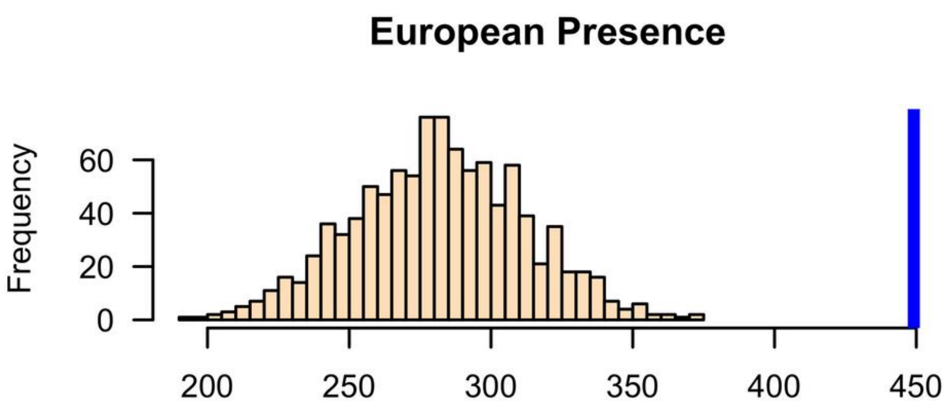
400
450


European Presence
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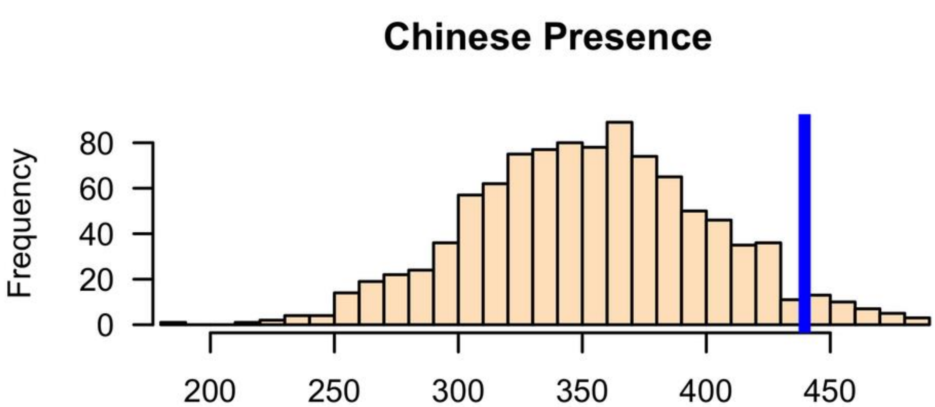
Chinese Presence
Frequency
0
20
40
60
80
200
250
300
350
400
450

Figure 8: Histograms of simulated average nearest-neighbour distances (ANN) values from 1000 simulations for three phases. X-axis values based on meteres represent ANN expected value. Each sample distribution presents the null hypothesis with the blue line indicating the observed ANN value

Our results offer tentative support for the hypothesis that foreign presence at Kiwulan influenced the shape of vessels made by the local Indigenous society. We find that vessel shapes were more standardized during the Chinese period than the European period. If increased shape standardization is a reliable indicator of craft specialization, then we may be seeing evidence of a shift from corporate (group-based, distributed, collective, cooperative) to network (individual-based, competitive) organization (Blanton et al., 1996; Feinman, 2010, 2000, 1995; Feinman et al., 2000). However, strong claims for an emergence of social inequality resulting from foreign contact at Kiwulan will need support from multiple and diverse sources of evidence that are beyond the scope of this paper.

Compared to other regions in Taiwan, European colonial influence was weak in Yilan due to isolation by the surrounding mountains, and the economic focus of the Spanish and Dutch who preferred northern and northwest Taiwan as their trading base (cf. Berrocal et al., 2020). Indigenous communities in Yilan experienced indirect influence from European trade networks and their colonial activities in a pericolonial context (cf. Acabado, 2017). In contrast to the Indigenous-European interactions at Kiwulan, interaction between Indigenous people and Chinese immigrants in the 19th century appears to have been more intense and direct. Historical records indicate that Chinese groups settled in Yilan and lived closely with Kiwulan Indigenous societies (Chen, 1963; Ke, 1993). This direct influence is reflected by the archaeological evidence of large amounts of Chinese porcelain and distinctive Chinese architectural bricks and tiles (Hsieh, 2009). Similarly, burials at Kiwulan in this later phase show the adoption of coffins in mortuary practices, which Chiu (2004) interprets as the adoption of a symbol of ethnic Chinese.

The shape variation reported here is subtle and invites consideration of another possible scenario, namely that the absence of major changes in vessel shape at Kiwulan may have been an act to show ethnic identity when experiencing foreign influences (cf. Torrence and A. Clarke, 2000b). Ceramic morphology could be a signal for communication between potters, such that repeating the same shape or slight modifications may have occurred in a non-deterministic way (Kubler, 1962). As the only type of locally made pottery throughout 600 years, the homogeneous and even more standardized shape in the Chinese period might convey some meaningful information about community identity. We recognize the decline in population may lead to a standardized shape, however, the evidence of ceramic spatial distribution shows a dispersed or random pattern across the whole area throughout three phases. This indicates manufacturing activities may be limited to the household scale and reflect a common, shared practice in the community. The standardization in vessel shape over time draws our attention to the endurance of traditional pottery production practices amid intrusions from Europeans and Chinese. In a culture contact situation, we speculate that social identity might have be expressed through material practices as a means of expressing cultural homogeneity and distinction from other groups (Voss, 2005). It is also important to recognize that social identity might be more complicated in a colonial context, and maybe representative of more than a colonized–colonizer or local/foreign dichotomy (Voss, 2008, 2005). For example, the Shamaoshan cemetery (BC 250 to 55 AD) in Southwest China suggests that the process of the incorporation of Southwest China into the Han Empire involved a century of conflicts, resistance, and acceptance among social groups with different identities, especially in the historical context of Han immigrants (Wu et al., 2019). At the Oconee Valley (AD 1540 to 1670) in the Southeastern United States, Indigenous endurance and resilience are indicated by the long-term persistence of mound use lasting for 130 years after the initial contact with European colonizers (Holland-Lulewicz et al., 2020). A similar dynamic may have occurred at Kiwulan, with vessel shape indicating both acceptance of foreign influence through increased shape standardization, and resistance through the overall continuity in vessel shape. Vessel shape may be viewed as a symbolic expression of Indigenous identity and social boundaries because shape is a highly visible trait compared with other features of pottery (cf. Roux, 2015). Although there is an increase in number of imported ceramics through time at Kiwulan, production of the same type of local ceramics was continuous, and increasingly standardized. This might imply not only the utilitarian function, but an intentional and increased emphasis on the local ceramic tradition, their cultural custom, as a response to intensified foreign contact (cf. Acabado, 2017). However, additional lines of evidence are necessary from Kiwulan to confirm this speculation.

Conclusion

This study demonstrated the first use of EFA on ceramic shapes to explore the emergence of ceramic specialization as indicative of foreign influences. Here, EFA is combined with significance tests for the equality of CVs of shape variables to provide a robust method for assessing differences in shape standardization. The direct relationship between foreign influences and standardization of ceramic shape was tested on ceramics from Kiwulan, a large Iron Age Indigenous settlement in northeastern Taiwan. Much lower variation in ceramic shape was identified during the period of Chinese presence. Our findings help to expand upon those factors that may lead to the standardization of ceramic production in a pericolonial interaction context. More homogeneous vessel shapes and sizes during the Chinese period, without any substantial changes in clay paste composition, production technique, and spatial distribution, suggest that shape standardization emerges from a combination of mechanical and intentional factors. Discrete groups of producers are not evident, favoring the role of intentional factors in this case. The distribution of ceramics in the Chinese period does not support clustered patterns of manufacturing locations, such as workshops. Instead, ceramic production is likely to have occurred in households. We speculate that the relatively homogeneous appearance of the vessels may suggest an expression of social identity or cultural boundaries in Indigenous societies through highly visible vessel qualities, such as shape. The symbolic value of these shapes may be heightened during periods of foreign contact in pericolonial contexts. Our analysis, with its openly available methods and data, is readily extensible to other pottery assemblages in the region to further explore related questions about craft specialization and standardization in ceramic assemblages. This study also broadens the GMM field by focusing on ceramic technologies, which may motivate more ceramic studies and become a promising branch parallel to current applications to lithic typology and bone morphology.

Acknowledgments

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