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Variation in North American dart points and arrow points when one or both are present

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ABSTRACT

The appearance of the bow and arrow in North America as a weapon-delivery system is predicted to have prompted an increase in variation among antecedent projectile points that tipped darts propelled by atlatls. Attributes of dart points are expected to display greater variation with the appearance of the bow as prehistoric artisans experimentally sought points that worked effectively as arrow points. Attributes of arrow points are predicted to also initially display much variation. Subsequent to the initial burst of variation, less-effective variants of attributes were winnowed out, causing a reduction in variation of attributes of both dart points and arrow points. Both coefficients of variation for individual attributes and summed coefficients of variation for multiple attributes of three sequences of projectile points from evolutionarily independent areas in North America confirm these predictions.

1. Introduction

North American archaeologists have long wondered when the bow and arrow appeared and replaced the atlatl-and-dart weapon system (Blitz, 1988). The question is not readily answered because bows, arrows, atlatls, and darts are rare in the archaeological record given the vicissitudes of time and preservation processes that are generally unfavorable to wood. The introduction of the bow and arrow is typically dated by inferring when arrow points first appeared using a variety of analytical techniques to distinguish between arrow points and dart points (Shott, 1996, 1997; Thomas, 1978; VanPool, 2006). The bow and arrow appeared at different times in different places, and in all cases the atlatl and dart continued to be used for several centuries subsequent to that appearance (e.g., Bradbury, 1997; Fawcett, 1998; Nassaney and Pyle, 1999).

Replacement of the atlatl and dart by the bow and arrow is a nearly ubiquitous example of the evolution of cultural traits, and as such, it provides an outstanding lens through which to study the general structure of cultural evolution. Here we examine the variation of projectile-point attributes within each weapon-delivery system in three culturally distinct geographic areas using chronologically ordered assemblages of points. We test predictions regarding patterns in the magnitude of variation created by innovation and selection operating on artifacts through time. In particular, we focus on the impact of the introduction of the bow and arrow, which represents the introduction of new adaptive space and attendant niche construction (Odling-Smee et al., 2003), on the variation in projectile points.

2. Theoretical perspective and predictions

We assume that cultural traits evolve in concordance with Darwinian evolution (Dunnell, 1978, 1980), which is a probabilistic rather than a deterministic process (Shanahan, 2003). Thus, evolution can be observed at the level of the changing membership of a population and does not predict the life history of any individual (Mills and Beatty, 1994). Four axioms follow from this assumption. First, cultural transmission creates artifact lineages (Lipo et al., 1997; Neiman, 1995). At a larger scale, groups of phylogenetically related lineages form traditions, or clades (Lipo et al., 2006; O'Brien, 2008). Second, the persistence of artifact classes over time monitors cultural transmission and heritability (Dunnell, 1978; Neiman, 1995). Each artifact identified as a member of a particular class is related phylogenetically to every other specimen within that class, given their shared attributes. Third, copying error, intentional or not, and experimentation create variation (Eerkens and Lipo, 2005; Schiffer, 1996). Fourth, selection reduces or stabilizes that variation

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(Dunnell, 1980; O'Brien and Lyman, 2000; VanPool, 2001; Wilhelmsen, 2001).

Archaeologists have long studied variation in artifact form but have typically recorded it as temporal shifts from one artifact type or class to another, ignoring for the most part within-class morphological diversity (Dunnell, 1986). In this paper we focus on morphological diversity manifested as variation in attributes of projectile points. Although variation will be continuously generated, we expect that the rate of morphometric change will be episodic rather than constant. Studies of modern material culture have found inventive activities to be "discernible as a clustering in time and space of similar inventions"—literally, a "burst of variation," termed *stimulated variation* (Schiffer, 1996, p. 656). The analogous process in biological evolution is adaptive radiation, during which organisms enter new niches (Futuyma, 1986; Grant, 1985). We believe a similar temporal dynamic attends stimulated variation. Perceived deficiencies in what is required of the performance characteristics of an artifact category result in a proliferation of variation (Petroski, 1992, p. 140), perhaps in a *cascade effect* as variables realign according to different performance requirements (Schiffer, 2005). Subsequently, variation will decrease as less-efficient variants cease to be replicated (VanPool, 2001; Wilhelmsen, 2001).

One temporal dynamic in human prehistory involved the appearance of a mechanically new weapon-delivery system—the bow and arrow—and the replacement of an older system—the atlatl and dart. Because of mechanical differences in the two weapon systems, attributes of dart points, especially those related to point size (arrow points are smaller than dart points) and the manner in which the points were fastened to shafts (hafting) had to be experimented with to find an effective combination of attributes and ultimately class(es) of points that could serve as arrow points (e.g., Beck, 1995, 1998; Bettinger and Eerkens, 1999; Hughes, 1998; Musil, 1988; Wilhelmsen, 2001). These efforts are archaeologically visible at the scale of taxonomic diversity (Lyman et al., unpublished data), at the scale of morphological diversity within classes (that is, in the degree of variation in attributes of points), or at both.

Our predictions regarding variation in point attributes are based on the assumption that the first arrow point was a descendant of an atlatl point within each sequence we examine. That is, we assume that the artisans did not copy an arrow point of which they were somehow aware (there was little or no horizontal transmission). In plain archaeological language, we assume that each of the particular cases we examine represents an instance of independent invention of arrow technology rather than diffusion of that technology into the site area from elsewhere. This assumption has implications for our expectations. Diffusion of a more or less perfected technology into a new area will likely be accompanied by minimal variation in the manifestations of that technology in the recipient area, and attribute states will be correlated with one another (Bettinger and Eerkens, 1999). Innovation, in contrast, will be accompanied by high levels of variation and weak to no correlation of attributes (Bettinger and Eerkens, 1999; Schiffer, 1996). Nevertheless, for various reasons—low fidelity transmission, selective neutrality of attributes, functionally independent attributes, imperfectly developed technology—diffusion can be accompanied by high levels of variation (Basalla, 1988; Schiffer, 2005).

Recent study of variation in attributes and their combinations as manifest on projectile points suggests analysts can distinguish functional from adaptively neutral traits (Eerkens and Bettinger, 2008). We do not pursue this analytical avenue here because our research question does not demand it. We are interested in the narrow question of how variation relates to innovation, in this case, the magnitude of variation in attributes of projectile points before, during, and after the appearance of the bow and arrow. Our predictions are founded on two well-documented aspects of North American prehistory. First, the dart-point lineage has a temporally deep history in North America, beginning as early as Paleoindian times (Dixon, 1999, pp. 151–153). And second, the arrow-point lineage began about 1500–1700 years ago in North America and spread over much of the continent rather rapidly (Blitz, 1988).

Our predictions concern the amount of variation manifest by individual attributes. First, we predict that variation of dart points should initially be high as artisans seek combinations of attributes that comprise effective dart points, but then that variation will gradually decrease as less-effective variants are winnowed out and only the most effective ones are replicated. The early history of the atlatl and dart is poorly known (e.g., we do not know when the atlatl was first invented), but they were present among New World Paleoindian hunters (Dixon, 1999). The initial variation in point morphology corresponding with the introduction of the atlatl and dart likely won't be reflected in collections dating to the Archaic and more recent periods, because much of it had already been winnowed through the development of effective dart points, which may have first appeared even before the appearance of humans in the New World. As a result, our model of variation in dart-point attributes is general with respect to the timing of maximum variation and of winnowing variation in attributes prior to the appearance of the bow and arrow. Thus our model in Fig. 1 should

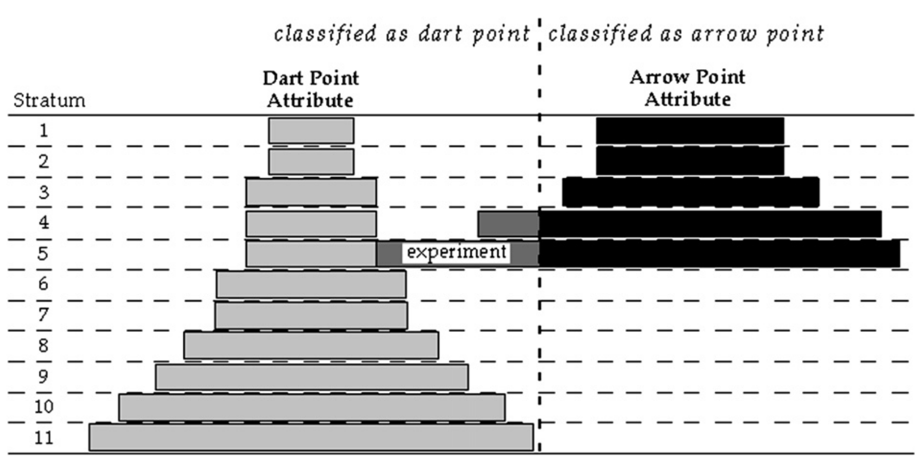

Fig. 1. Modeled expectations of variation in attributes of dart points and of arrow points over time. Bar width signifies ordinal-scale variation; wider bars denote greater variation. Note that it is probable that some early arrow points will be misclassified as dart points, and some dart points will be misclassified as arrow points as artisans "experiment" with the magnitudes of attributes.

Table 1
Verkamp Shelter, Missouri, projectile-point frequencies per cultural horizon

Cultural horizon	Age (RCYBP)	N of dart points	N of arrow points
4	1000–?	71	103
3 (Woodland)	?–1000	80	0
2 (Woodland)	2500–?	59	19
1 (Late Archaic)	3500–2500	47	0

Table 2
Mummy Cave, Wyoming, projectile-point frequencies per stratum

Stratum	Age (RCYBP)	N of dart points	N of arrow points
1–2	?–370	0	22
3	1230	0	64
4–5	2820–2050	35	0
6–7	4420–4090	72	0
8–12	6780–4640	105	1[a]
13–23	9250–7630	32	0

[a] Not included in calculation of CCVs.

be viewed as ordinal scale on both the horizontal and the vertical axes.

Second, the variation of at least some attributes of dart points should increase coincident with the appearance of the bow and arrow, as artisans seek attribute variants that, when combined into a single specimen, work well with the new weapon-delivery system (Fig. 1). Initially, effective dart points may be used to tip arrows, making the first arrow points and contemporaneous dart points indistinguishable. Given differences in performance requirements of the weapons, such dart-as-arrow points would be only marginally effective (Hughes, 1998; VanPool, 2003; Wilhelmsen, 2001). Both intentional experimentation and unintentional copying error will increase variation in early arrow points (Bettinger and Eerkens, 1999; Eerkens and Lipo, 2005, 2007). Variation will subsequently decrease as selection winnows ineffective variants and experimentation slows, although variation in point attributes will be continually generated by copying error, further experimentation, point rejuvenation, and the like.

Third, we predict that the magnitude of variation of arrow-point attributes will initially be great but subsequently decrease as effective attribute combinations are selected for and less-effective combinations are winnowed out. Variation can be manifest in metric attributes (e.g., length, width, weight), in qualitative attributes (e.g., presence/absence of notches or a stem), or in both. Experiments by Cheshier and Kelly (2006) exemplify what we mean by effective attribute combinations. They found that projectile points with a high thickness:length ratio were more durable than points with a low ratio.

Fourth, we predict that variation in individual attributes within both dart points and arrow points should decrease as less-effective variants are winnowed out—that is, within-kind variation should decrease and become more standardized as a result of selection (VanPool, 2001). It is important to note that this prediction and the preceding one assume that individual attributes are not mechanically linked to one another such that change in one causes a change in another. We recognize that this assumption is to some degree false (Beck, 1995; Hughes, 1998; Wilhelmsen, 2001). Maximum length of a point will, for example, be correlated with point weight to some degree because both are measures of size. We thus examine the variation of each attribute individually as well as the total variation of all attributes, recognizing that the magnitude of total variation may be a function of a relationship between the variation of two or more attributes.

Our predictions assume accurate classification of individual points as either dart or arrow points. We suspect, however, that the initial arrow points will resemble useful dart points and hence may be classified by the archaeologist as dart points. Dart points are typically distinguished from arrow points by weight (dart points > 3 g $>$ arrow points; e.g., Hughes, 1998; VanPool, 2003) or shoulder width (dart points > 2 cm $>$ arrow points; e.g., Thomas, 1978). Size criteria allow distinction of many dart points from arrow points in assemblages containing both, but it is also clear that some points will be incorrectly classified. For example, Shott (1997, p. 98) evaluated the 2-cm shoulder-width criterion using hafted archaeological specimens that were clearly associated with one of the weapon systems and found that 8% of arrow points and 23% of dart points were incorrectly classified. Instances of such incorrect classification are equivalent to specimens that represent experimental efforts to create, say, an arrow point based on a model of a dart point. It is precisely such variation in which we are interested.

Hughes (1998) examined variation in projectile-point attributes regardless of whether a point was an arrow point or a dart point. We are interested, however, in the influence of a new technology—in this case, a new weapon-delivery system—on variation within its antecedent ancestral technology and also within the new technology itself and how the two are related. This demands that we distinguish between arrow points and dart points rather than examine undifferentiated points. Again, though our predictions assume accurate distinction of dart points and arrow points, our predictions are sufficiently robust to accommodate some error.

Our predictions are predicated on the notion that morphological variation will respond to changes in selective environments by either increasing or decreasing. Our expectations concern functional traits—those whose replication is influenced by selection as opposed to just transmission (Cochrane, 2001; Lipo et al., 1997; Neiman, 1995). Previous research on projectile points (especially Beck, 1995, 1998) suggests that many of the attributes' archaeologists routinely use to define point classes are indeed functional. Some attributes and attribute combinations may, however, have the appearance of styles—they are stochastically distributed across time and space—because they are mechanically linked to other traits (Schiffer and Skibo, 1997), resulting in trade-offs in performance of some attributes. Beck (1998) demonstrates, for example, that several of the attributes of projectile points that we track are mechanically linked (see also Cheshier and Kelly, 2006). We ignore the potentially significant analytical distinction of functional from stylistic attributes and focus instead on variation in individual attributes. We do so because we predict that there is an overall pattern in attribute variation. If there is, then it can be suggested that there is a general evolutionary pattern surrounding the introduction of the bow and arrow, and perhaps the introduction of new technology generally. If not, then explanations will require more particularistic models.

3. Analytical methods

To monitor variation at the scale of specimen morphology, or individual attributes, we calculated a corrected coefficient of variation (CCV) for each of multiple attributes of dart points and arrow points (after VanPool, 2001, 2003). We use the CCV rather than the more familiar coefficient of variation to account for small sample sizes (Sokal and Rohlf, 1981, pp. 58–60). The formula for the CCV is taken from Haldane (1955) and is

$$\mathrm{CCV} = [1 + (1/4n)][(S/\mathrm{avg})100]$$

where n is the sample size, S is the standard deviation, and avg is the mean. Coefficients of variation are unit free, and take into account the absolute size of the variables being measured by standardizing the standard deviation using the mean. They thus allow variation across quite different variables—say, length and weight—to be directly compared. Biologists have devoted much effort to evaluating the analytical value of the CV (and CCV) and to developing ways to compare CVs statistically (see Plavcan and Cope, 2001 and references therein). We follow their lead here and use a *t*-test to compare CCVs (Zar, 1996, pp. 144–146) and to determine if the magnitude of change in CCVs of individual attributes is significant from one period to the next. Change from one value to another may, however, be statistically insignificant but evolutionarily significant. That is, short-term evolutionary change in artifacts may be of a magnitude below statistical detectability as it sometimes is in biological lineages (e.g., Grant and Grant, 2002). To assist with detecting a long-term evolutionary trend (the constituent short-term changes need not be statistically significant), we plot the magnitude of variation against time (e.g., Gould, 1988).

Plotted against temporal periods, shifts in CCV values illustrate the history of morphological diversity (VanPool, 2003). Previous investigators have examined one attribute at a time (e.g., Eerkens and Bettinger, 2001; Eerkens and Lipo, 2005; Hughes, 1998). We examine the variation evidenced by multiple attributes simultaneously over time using a technique similar to one used by biologists (Yablokov, 1974). One difference between what biologists have done and what we do here is that we sum all CCVs per time period to evaluate overall variation independently within dart points and within arrow points, though interpretation of the $\sum$CCVs must be tempered with acknowledgment that the contributing attributes might be mechanically linked. We use a centered-bar graph to depict the magnitude of variation in each attribute in each stratum and to assist with visualizing trends in the variation of individual attributes.

Because we use data gathered by others, it is important to indicate why we discuss the attributes that we do. At one site (Gatecliff Shelter), analytical interest was in attributes that distinguished temporally distinctive or diagnostic types. At another (Mummy Cave), temporally sensitive types and differences between arrow points and dart points were of interest. At the third site (Verkamp Shelter), the interest was parallel to ours. Despite these differences, the attributes measured were similar across all three. All included length (maximum), width (maximum), and thickness. Two studies included neck width, base width, and base length. Width and thickness influence penetration, as does neck width insofar as it is related to shaft diameter. Width and length are related to the amount of cutting edge and the severity of the wound inflicted (Hughes, 1998; Wilhelmsen, 2001). Ease of manufacture and durability demand compromises in some performance attributes, thus attributes of effective points may vary to some degree simply depending on contingencies of the moment and what artisans desired.

Table 3
Gatecliff Shelter, Nevada, projectile-point frequencies per cultural horizon

Cultural horizon	Age (RCYBP)	N of dart points (N of Elko Corner Notched)	N of arrow points (N of Rosegate)
1	700–500	1	19
2	700	1	22 (19)
3	1300–700	3 (3)[a]	26 (24)
4	1900–?	67 (44)	1 (1)[a]
5	?	100 (70)	0
6	3250–?	57 (44)	3
7	3300–3250	39 (36)	0
8	3350–3300	38 (12)	0
9	3450–3350	17 (1)	0
10	4100–3450	1	0
11	4300–4150	0	0
12	5050–4300	5	0
13	5150–5050	0	0
14	5300–5150	6	0
15	5400–5300	1	0
16	5550–5400	0	0

[a] Not included in calculation of CCVs.

The CCVs we present reflect the history of morphological diversity as perceived through the filters of classification (how analysts measured attributes) and sampling (which portions of a lineage are represented). These filters demand several analytical conventions. For one, we treat each clade as if the earliest period represented by projectile points is the one in which dart points first appear, though it is clear that the atlatl was present before the earliest materials we examine. Similarly, all sequences of projectile points are truncated in the early historic period (16th and 17th centuries A.D.), so the last period when projectile points are observed may not represent the natural end of the lineage. We do not expect a perfect match between a data set and our model or our predictions for these reasons.

4. Materials

Because the topic we address has seldom been considered, appropriate data sets for testing of our predictions are scarce. Here we use three sets, each of which reveals critical aspects of the evolutionary history of prehistoric weapon-delivery systems. The data sets come from widely separated areas, which reduce the effects of horizontal transmission in structuring the prehistoric point populations. This is not to say that point technology did not diffuse horizontally (geographically) or that there are no means available to identify diffusion in the archaeological record (see, for example, Bettinger and Eerkens, 1999; Eerkens and Bettinger, 2008). But because we are interested in how variation is influenced by innovation and subsequent vertical transmission, samples from widely separated locales are preferred.

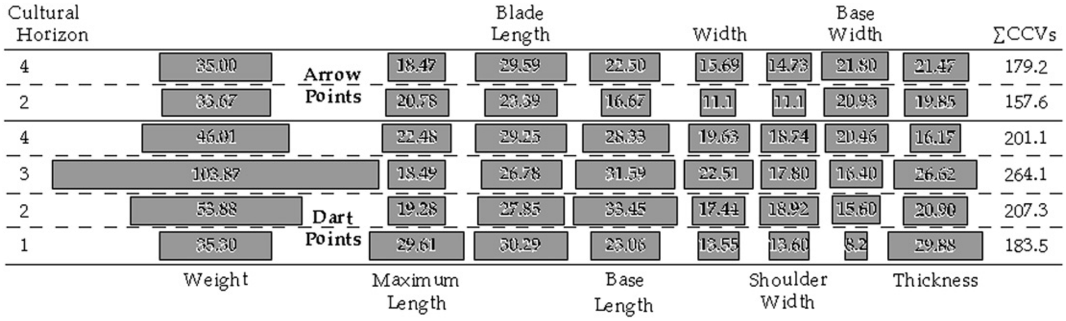

Fig. 2. History of variation (CCVs) in eight attributes of arrow points and dart points from Verkamp Shelter, Missouri. All points are included regardless of class.

Table 4
Statistical comparisons (Student's *t*) of corrected coefficients of variation per attribute at Verkamp Shelter

Strata compared	Weight	Maximum length	Blade length	Base length	Width	Shoulder width	Base width	Thickness
4–2 (Arrow points)	0.19, $p > 0.5$	0.673, $p = 0.5$	1.105, $p > 0.2$	1.415, $p > 0.15$	1.685, $p > 0.05$	1.381, $p > 0.15$	0.211, $p > 0.5$	0.405, $p > 0.5$
4–3 (Dart points)	4.417, $p < 0.001$	1.635, $p > 0.1$	0.71, $p > 0.4$	0.849, $p > 0.3$	1.125, $p > 0.2$	0.429, $p > 0.5$	1.854, $p > 0.05$	3.914, $p < 0.001$
3–2 (Dart points)	20.572, $p < 0.001$	0.342, $p > 0.5$	0.301, $p > 0.5$	0.43, $p > 0.5$	1.988, $p < 0.05$	0.485, $p > 0.5$	0.421, $p > 0.5$	1.845, $p > 0.05$
2–1 (Dart points)	2.451, $p < 0.02$	2.968, $p < 0.01$	0.565, $p > 0.5$	2.147, $p < 0.05$	1.793, $p > 0.05$	2.207, $p < 0.05$	4.193, $p < 0.001$	2.447, $p < 0.02$

Verkamp Shelter is in central Missouri (Fuld, 2006). Its 3-m-thick deposits were stratified, and the original investigator sorted the strata into five cultural horizons. No radiometric dates are available for the site, but artifact cross-dating indicates people used the shelter over the past 6000 years. No measurable projectile points were recovered from the oldest cultural horizon, but 398 points from the most recent four horizons were studied to monitor morphological variation during the shift from dart points to arrow points (Fuld, 2006). One hundred and twenty-four arrow points and 274 dart points were distributed across the cultural horizons; frequencies in Table 1 sum to fewer points because of unclear provenience of some specimens. The absence of arrow points from cultural horizon 3 is likely the result of sampling error (no measurable arrow points were recovered), stratigraphic mixing, and misclassification of some arrow points as dart points. Metric data for projectile points from Verkamp Shelter are available from Fuld (we have her contact information).

Mummy Cave is in northwestern Wyoming (Wedel et al., 1968). The 8-m-thick deposits were laid down over the last 9200 RCYBP and consisted of more than 50 distinct strata, approximately half of which produced cultural material (Husted and Edgar, 2002). Projectile points from the site were analyzed by Hughes (1998), who provided us with her unpublished data on attributes of individual points. Three hundred and thirty-one projectile points recovered from the site were sufficiently complete to be classified and used in our analysis (Table 2). We classified specimens as either arrow points or dart points based on the culture-historical types recognized by Hughes (unpublished data). We lumped some adjacent strata to increase sample sizes. Unlike the other assemblages, there is no recognized period during which both the atlatl and dart and bow and arrow were used. Instead, with a single exception, arrow points are unique to strata 1 through 3, which do not contain dart points. The single arrow point stratigraphically associated with dart points (Table 2) was omitted from calculations of CCVs; its inclusion in the calculation does not change any CCV significantly (amount of change per attribute < 0.7%). Metric data for Mummy Cave projectile points are available from Hughes.

Gatecliff Shelter is in central Nevada (Thomas, 1983). Its 10-m-thick sedimentary record includes 56 individual strata, among which the excavators identified 16 cultural horizons. The horizons span approximately the last 5500 years (Table 3). Four hundred and seven projectile points were distributed among the cultural horizons (Thomas and Bierwirth, 1983). Three classes of arrow points and seven classes of dart points are represented (Bettinger et al., 1991; Thomas, 1978, 1981). CCVs per attribute were calculated for dart points in horizons 4–9 and for arrow points in horizons 1–3. Small sample sizes prevented the calculation for dart points in horizons 1–3 and arrow points in horizons 4–9. Inclusion of arrow points from horizons 4–9 and of dart points from horizons 1–3 in calculations greatly alters the CCVs for width, basal width, and neck width in most cases. This is not at all surprising given that (shoulder) width and neck width (and the related base width) are typically used to distinguish dart points from arrow points (see above). Metric data for Gatecliff projectile points are available in Thomas and Bierwirth (1983).

5. Results

As outlined above, we expect that variation in dart points before the introduction of the bow and arrow will be limited or perhaps decreasing as a result of selection for effective dart points. With the introduction of the bow and arrow, total morphological variation should increase in both dart points and arrow points resulting from experimentation. Given adequate time (i.e., evolutionary opportunity), variation in dart points should decrease and eventually be limited around those optima that result in effective dart points and the variation in arrow points should decrease as effective attribute combinations for arrows develop and are favored by selection.

The expected pattern of variation is reflected at Verkamp Shelter (Fig. 2). The appearance of arrow points in horizon 2 corresponds with an increase in total variation of dart points as indicated by ∑CCVs in horizons 2 and 3. This trend is especially well reflected by the weight attribute. Weight is one of the most important determinants of projectile performance characteristics and also is linked to all of the other traits (all other variables being equal, thinner points weigh less than thick points and longer points weigh more than shorter points). Thus, weight would have been a focus of experimentation and been indirectly impacted by experimentation with other attributes, causing it to vary considerably as people tinkered with point design to make useful arrows. The increase in ∑CCV from horizon 1 through horizon 3, followed by a decrease in ∑CCV for dart points in horizon 4, meets our predictions.

Within the weapon systems, CCVs for seven of the eight metric attributes measured on arrow points from Verkamp Shelter

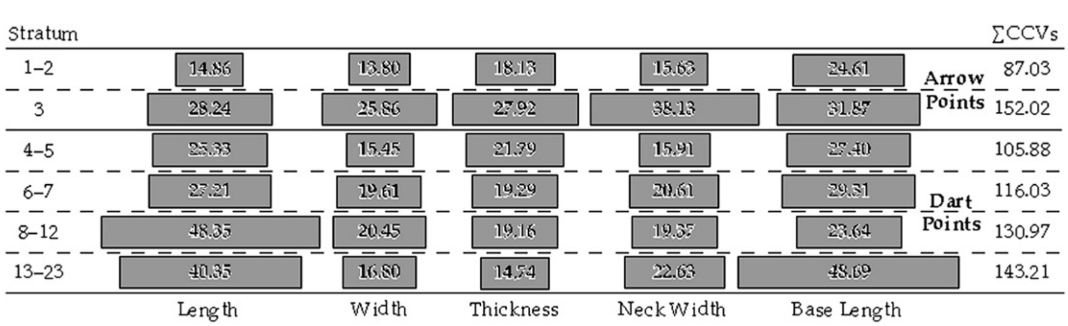

Fig. 3. History of variation (CCVs) in five attributes of arrow points and dart points from Mummy Cave, Wyoming. All points are included regardless of class.

Table 5
Statistical comparisons (Student's *t*) of corrected coefficients of variation per attribute at Mummy Cave

Levels	Length	Width	Thickness	Neck width	Base length
1&2 to 3	2.158, $p < 0.05$	2.622, $p < 0.02$	1.92, $p > 0.05$	2.961, $p < 0.01$	1.076, $p > 0.2$
3 to 4&5	0.462, $p > 0.5$	2.558, $p < 0.02$	1.439, $p > 0.15$	4.516, $p < 0.001$	0.856, $p > 0.15$
4&5 to 6&7	0.276, $p > 0.5$	1.430, $p > 0.15$	0.825, $p > 0.4$	1.655, $p > 0.1$	0.50, $p > 0.5$
6&7 to 8–12	3.227, $p < 0.001$	0.365, $p > 0.5$	0.059, $p > 0.5$	0.508, $p > 0.5$	1.75, $p > 0.05$
8–12 to 13–23	0.452, $p > 0.5$	1.209, $p > 0.2$	1.619, $p > 0.1$	0.853, $p > 0.3$	83.5, $p < 0.001$

increase from cultural horizon 2 to horizon 4 (Fig. 2), although none of the changes is statistically significant ($p > 0.05$; Table 4). We take the increased variation from the introduction of the bow and arrow to represent stimulated variation reflecting the search for effective values of attributes and effective combinations thereof, which is consistent with our expectations. Unfortunately, we cannot test our prediction that CCVs for arrow points will decrease over time because Verkamp Shelter lacks stratum 3 arrow points and also lacks the most recent era of the evolutionary sequence.

The absence of a consistent trend in the CCVs of dart-point attributes (with the exception of basal width) is likewise consistent with our expectations (Fig. 2). CCVs for five of eight attributes increase from horizon 1 to horizon 2 (four are statistically significant) coincident with the introduction of the arrow. We propose that this variation reflects experimentation with arrow points that resemble effective dart points (and are therefore classified archaeologically as dart points). CCVs continue to increase substantially through horizon 3 and then decrease as we expect in horizon 4, largely as the result of significant decreases in the variation of weight and thickness.

Variation in maximum length and thickness of Verkamp Shelter dart points decreases significantly from horizon 1 to horizon 2 (Table 4), contrary to our expectations for increased variation. This decrease may reflect the size limits of dart points given that dart points can only be reduced so much in size before they are no longer consistently effective as a dart points and are not classified as dart points by archaeologists. If experimentation using effective dart points with the bow and arrow led quickly to the use of smaller points, which would be more effective with arrows, variation in length and thickness might decrease as well. Ultimately, then, the pattern reflected in the Verkamp Shelter data closely, albeit not perfectly, fits our expectations.

The CCVs of dart-point attributes at Mummy Cave decrease in eight of 15 instances (three temporal changes, five attributes) over time (Fig. 3). Such changes in variance are suggestive of drift resulting from copying error (e.g., Eerkens and Lipo, 2005), but the total variation suggests there is more to it than that. The $\sum$CCVs of dart-point attributes decrease monotonically over time—a long-term trend. Stabilizing selection seems to have worked on multiple attributes in combination—which is precisely what a projectile-point comprises—creating the patterned decrease in $\sum$CCVs from stratum 23 through stratum 4 (Fig. 3). Arrow points appear in stratum 3, and each of the five measured attributes displays an increase in variation relative to its preceding variation in dart points with the increases in variation of width and neck width being statistically significant (Table 5). The increase in $\sum$CCVs coincident with the appearance of arrow points is as we predicted. Artisans who were depositing the stratum 3 points were experimenting as they sought a combination of attribute states that comprise an effective arrow point. Even if some of the points in stratum 3 represent dart points (they all belong to types thought to represent arrow points), our predictions are still met. Finally, the variation in all five attributes decreases from stratum 3 to strata 1&2 (three of five are statistically significant decreases; Table 5), meeting our prediction that variation in arrow points will decrease as ineffective variants are winnowed out.

In an earlier study of the Gatecliff Shelter projectile points we found a correlation between the number of projectile points and the richness of classes of points ($r = 0.744$, $p < 0.001$), suggesting that temporal fluctuation in the diversity of the clade may be a function of sample size (Lyman and O'Brien, 2000). Because of this potentiality, and the small samples of points in cultural horizons 10–16, we consider only the points from horizon 1 to horizon 9.

As in biological evolution, a descendant artifact form requires an antecedent or ancestral artifact form (Basalla, 1988; Eerkens and Lipo, 2007). Part of the better-known history of projectile points in the Great Basin is that the class of dart point known as "Elko Corner Notched" appears to have been ancestral to the class of arrow points known as "Rosegate" (Beck, 1995; Bettinger and Eerkens, 1999). The latter have been characterized as small versions of the former (Bettinger and Eerkens, 1999). Variation in eight attributes of each of these two classes at Gatecliff Shelter displays intriguing patterns. First, very few of the changes are statistically significant (Table 6). However, the CCVs for Elko Corner Notched (dart) points decrease in 20 of 24 cases from combined horizons 8 and 9 (lumped for reasons of sample size) to horizon 5 (eight attributes, three time changes each), a statistically significant result ($\chi^2 = 10.67$, $p < 0.005$) suggesting an evolutionary trend in variance that is otherwise largely statistically undetectable (Grant and Grant, 2002). Such a trend is not unexpected as artisans learned the attributes that together form the most efficient dart point (Fig. 4)—expectations borne out by experimental and computer simulation (Mesoudi and O'Brien, in press). This trend meets our prediction of winnowing of variation in dart points prior to the appearance of the bow and arrow.

As predicted, the $\sum$CCVs for dart points increase from horizon 5 to horizon 4, likely coincident with the introduction of the bow and arrow (Table 3). Arrow points first appeared in the Great Basin about A.D. 400 (Kelly, 1997), perhaps when horizon 4 and certainly when horizon 3 was being deposited. Four of the CCVs for eight attributes of Rosegate (arrow) points increase, and four CCVs decrease from horizon 3 to horizon 1/2. Recognizing that there are no

Table 6
Statistical comparisons (Student's *t*) of corrected coefficients of variation per attribute at Gatecliff Shelter

Horizons compared	Maximum length	Axial length	Maximum width	Basal width	Neck width	Thickness	Distal shoulder angle	Proximal shoulder angle
1&2 to 3	1.665, $p > 0.1$	1.706, $p > 0.05$	0.226, $p > 0.5$	0.544, $p > 0.5$	0.296, $p > 0.5$	0.152, $p > 0.5$	0.261, $p > 0.5$	2.593, $p < 0.02$
3–4	0.04, $p > 0.5$	0.041, $p > 0.5$	0.852, $p > 0.3$	2.361, $p < 0.05$	1.709, $p > 0.05$	0.463, $p > 0.5$	0.125, $p > 0.5$	0.926, $p > 0.3$
4–5	0.964, $p > 0.3$	1.067, $p > 0.2$	2.059, $p < 0.05$	2.284, $p < 0.05$	0.905, $p > 0.3$	1.321, $p > 0.15$	1.016, $p > 0.3$	2.439, $p < 0.02$
5–6	1.12, $p > 0.2$	1.519, $p > 0.1$	0.963, $p > 0.3$	0.278, $p > 0.5$	0.285, $p > 0.5$	0.047, $p > 0.5$	0.73, $p > 0.4$	0.902, $p > 0.3$
6–7	0.381, $p > 0.5$	0.261, $p > 0.5$	0.171, $p > 0.5$	1.148, $p > 0.2$	0.682, $p > 0.4$	0.443, $p > 0.5$	0.48, $p > 0.5$	0.657, $p > 0.5$
7 to 8&9	0.143, $p > 0.5$	0.448, $p > 0.5$	0.564, $p > 0.5$	0.363, $p > 0.5$	1.467, $p = 0.15$	0.099, $p > 0.5$	0.14, $p > 0.5$	0.008, $p > 0.5$

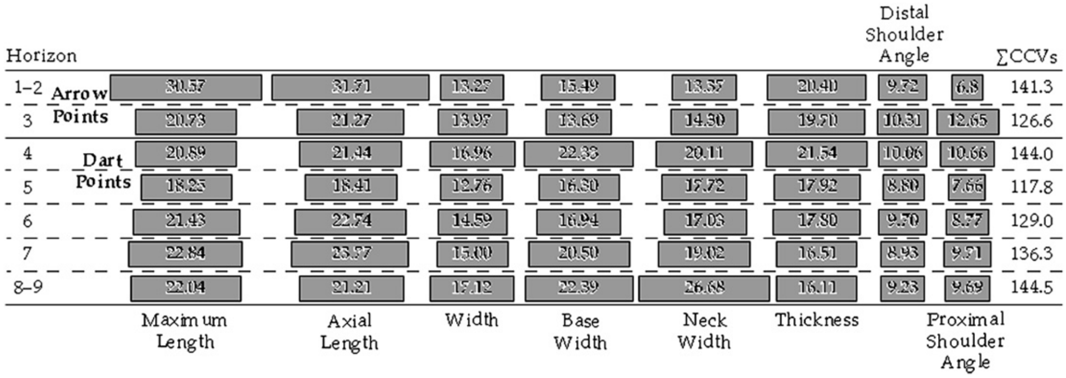

Fig. 4. History of variation (CCVs) in eight attributes of arrow points and dart points from Gatecliff Shelter, Nevada. Only the Elko Corner Notched (dart) point and Rosegate (arrow) point classes are included.

Rosegate (arrow) points in horizon 1 (Table 3), we believe the artisans were still experimenting and learning the size of attributes that in combination produced an effective arrow point when horizon 2 was being deposited. The predicted reduction in the ∑CCVs is not apparent because the most recent portion of the sequence is missing, and this is when we expect stabilizing selection to have winnowed out at least some of the ineffective variants.

6. Discussion and conclusion

Archaeologists have typically explored the taxonomic diversity of artifacts for chronometric purposes, ignoring within-taxon morphological diversity except to bemoan its influence on systematics (Lyman et al., 1997). The history of the diversity of artifacts at both scales has only recently been seen to be of analytical import and to provide unprecedented insight into the evolution of material culture (e.g., Beck, 1995; Eerkens and Bettinger, 2001; Eerkens and Lipo, 2005; Lake and Venti, in press; Lyman and O'Brien, 2000; Schiffer and Skibo, 1997; VanPool, 2001, 2003).

Elsewhere, we predicted that diversity in dart-point classes would initially be high and would subsequently decrease, perhaps stabilizing prior to the appearance of the bow and arrow. Dart-point class diversity would, we thought, increase coincident with the appearance of the bow and arrow and then decrease shortly thereafter (Lyman et al., unpublished data). Diversity in dart-point classes should increase as artisans experiment with modifying dart points into effective arrow points. Thus, diversity in projectile points in general (dart points + arrow points) should be high at the time when the bow and arrow first appear but then decrease as some classes of dart points and less-efficient classes of arrow points cease to be manufactured. Our predictions were largely met by six independent sequences of projectile points from the western United States (Lyman et al., unpublished data), including points from Mummy Cave and Gatecliff Shelter. That our predictions were met by multiple data sets suggest that the effects of the general evolutionary processes of innovation and winnowing are widespread. This discovery prompted our analysis of the variation in attributes within the general categories of dart points and arrow points.

The three collections of projectile points we consider here were limited to those with detailed morphometric data for individual specimens. These collections originate in locales that were relatively independent of one another in terms of their evolution. The data indicate that the magnitude of variation in attributes of projectile points responds in predictable ways to changes in the selective environment. The change in selective environment comprised the shift from the atlatl and dart to the bow and arrow as the dominant weapon-delivery system. Variation in dart-point attributes tends to be stable or decrease in early parts of all sequences. Total variation (∑CCVs) increases coincident with the appearance of the arrow, as dart points are redesigned (likely through trial and error) to perform effectively with the new weapon system.

The change in selective environment resulted in considerable variation in arrow points. The CCVs of many attributes of arrow points are relatively large in the early strata in which arrow points first appear. We found indications of our prediction that high variation in arrow points would decrease as less-effective variants were selected against though our results are not universal on this likely because the recent portions of two evolutionary sequences (Verkamp, Gatecliff) are missing. Given that the overall patterns of variation we predicted are represented among the point assemblages we consider, we suspect that those patterns may be typical of the evolution of projectile points in general and perhaps other manifestations of material culture when innovative technologies are introduced. Total variation (∑CCVs) will initially be great, and many, though perhaps not all, attributes will display large coefficients of variation. Subsequently, those attributes will display CCVs of lesser magnitude, and the total variation represented by the ∑CCVs will decrease as less-effective variants are winnowed out.

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