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Practice Makes Within 5% of Perfect: Visual Perception, Motor Skills, and Memory in Artifact Variation[1]

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Variation in artifact assemblages has been an important source of information for reconstruction of prehistoric behavior. Archaeologists have used variation to construct typologies and to document changes in artifact types through time. More recently they have used variation, particularly standardization (i.e., limited variation), to investigate how craft production is organized in particular societies. For example, ceramicists often use standardization to assess whether the production process involved craft specialists and how the organization of craft workers relates to the development of complex social organizations (e.g., Arnold 1991, Blackman, Vandiver, and Stein 1993, Costin and Hagstrum 1995, Longacre, Kvamme, and Kobayashi 1988, Longacre 1999, Rice 1991). Similarly, archaeologists have studied standardization in lithic and bone and antler assemblages to understand how tool kits were designed and how changes in standardization relate to settlement patterns, subsistence strategies, gender relations, social hierarchy, and even cultural transmission (e.g., Bettinger and Eerkens 1997; Chase 1991; Dobre 1995; Eerkens 1997, 1998; Hayden and Gargett 1988).

Less attention has been paid to one of the main sources of variation in the archaeological record—human error. In particular, few studies have considered how and why humans make errors, or the limits of human ability to make artifacts of a particular size and shape. This study, then, asks: How standardized is a "standardized" set of artifacts, and is there a basic measurement that describes the minimum amount of variation attainable by humans producing artifacts by hand?

Analysis of human perceptual abilities would seem to be the appropriate starting point. Perception is intimately tied to standardization, since manufacturers and consumers of goods must perceive, primarily visually, whether the object they have produced or acquired is the right size and shape. They do this either by direct visual comparison with an independent standard (i.e., an object that is known to be the right size and shape) or by indirect comparison with a mental template. Standardization, as measured by archaeologists, ensues when producers consistently match products with an independent standard or mental template, thereby reducing variation in those products.

Archaeological studies often present measurements such as standard deviation or coefficient of variation to describe variation within a set of artifacts (i.e., pots, projectile points, beads) and attributes (i.e., diameter, thickness, length). However, archaeologists rarely speculate on what these values mean, other than that they are more or less than some other set of artifacts or attributes. This paper explores how visual perception, memory, and motor skills contribute to variation in artifacts as a raw material is transformed into the desired object. To address this issue, a simple experiment was designed to determine the accuracy of human memory of common and standard objects and establish how well humans can transform a mental image of such an object into a physical object of the same size and shape.

WEBER FRACTIONS AND COEFFICIENTS OF VARIATION

Psychologists have been interested in the limits of human perceptual abilities for some time. In the early part of the 19th century, researchers noted that human perception of various stimuli was imprecise, as shown by differences between estimated and actual magnitudes of stimulus input (i.e., heat, weight, brightness of light, etc.). Of particular interest to some of these scholars was the level of imprecision of different sensory systems relative to one another and the relation between error in estimation and the magnitude of the stimulus. By the 1830s E. H. Weber (Weber 1834; see Coren, Ward, and Enns 1994:39–43) had noticed that absolute error in human perception rose linearly with the magnitude of the signal or item being perceived. For example, Weber asked human subjects to judge the difference in heaviness between two weights or the difference in length between two lines. His results suggested that if the weights or lines differed by more than 3% a difference in magnitude was readily detected, while those differing less than this amount were perceived as equal. This suggested that the maximum accuracy of human perception of weight and

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length without the presence of a scale or ruler was not absolute but related to what was being perceived and its relative magnitude. These 3% values for weight and length are referred to in the psychophysical literature as Weber fractions (Coren, Ward, and Enns 1994, Norwich 1983, Ross and Gregory 1964). Weber fractions now exist for a wide variety of human sensory systems, including sensation of pain, heat, scent, brightness of light, and sound. Comparison of Weber fractions demonstrates that certain sensory systems, such as length perception and electric shock sensation, are more accurate than others, such as taste and sensation of brightness (see Coren, Ward, and Enns 1994:39–43; Teghtsoonian 1971).

The Weber fraction for length estimation has important implications for archaeological studies of standardization (Eerkens and Bettinger n.d.). First, if humans are trying to produce artifacts of a particular size, the closest they can get without an independent scale or ruler is within 3%. Difference less than this is not noticeable. If people are attempting to estimate size this will correspond to a sample coefficient of variation of roughly 1.5–1.7% (depending slightly on the underlying sample distribution, whether normal, uniform, etc.) and represent the ultimate limit of the ability to differentiate one-dimensional size. Second, since error and size are often correlated in a linear fashion (see Bettinger and Eerkens 1997, Eerkens and Bettinger n.d.), the coefficient of variation is an excellent statistic for assessing and comparing standardization in artifact assemblages. Conveniently, archaeologists often report this value or present mean and standard deviation measurements that can be used to determine it.

Thus, at a basic level, there is a critical threshold in human visual perception that limits our ability to make artifacts consistently the same size and shape without reference to an independent standard or ruler (i.e., without direct comparison). Yet, while the ability to differentiate length is an important factor that contributes to error (i.e., variation) during the manual manufacture of artifacts, other features, such as accuracy in memory, the ability to convert a mental template or image to a physical object, and motor control during production, play a role as well. These processes are likely to contribute to error above and beyond basic visual perceptual abilities. For example, studies suggest that error in size estimation of a remembered object increases with time from the initial observation (Kerst and Howard 1978, 1984; Moyer et al. 1977; Pelli and Farell 1992). In these studies subjects were asked to remember the length of a line and then state whether it was longer or shorter than a second line shown later. The results demonstrate that lines must differ by even more than 3% for the two to be perceived as different in length and that an increase in the length of time elapsed between initial viewing and comparison with a new line increases the imprecision in estimates of line length.

While these studies have implications for archaeological research on artifact standardization, they are not readily applicable because they do not mimic the exact context of artifact production typical of archaeological situations. In particular, most studies focus on the ability to differentiate absolute line length and do not consider how the transformation of an idea or mental template into a physical object through manual manipulation of a raw material contributes to error. I was unable to find results of published psychophysical experiments that suggested how visual perception, memory, and motor skills together contribute to error or what the minimum variation under such circumstances should be. As a result, I undertook a series of experiments to address this topic.

METHODS

Thirty individuals, 17 women and 13 men, were asked to participate in an experiment to examine accuracy in the reproduction of standard objects from memory. These subjects, graduate and undergraduate students from the University of California at Santa Barbara ranging in age from 18 to 54 (18 to 35 for females and 19 to 54 for males), were given a standard white sheet of paper (8.5″ × 11″) and scissors and asked to cut from memory figures the size and shape of a dime, a quarter, a business card, a 3.5″ floppy disk, a dollar bill, and a CD case. They were informed they could recut a figure until they were satisfied that it approximated the size and shape of the item requested. This task was referred to as "trial 1."

Next the subjects were asked to repeat the experiment, this time having inspected a physical specimen of each item (i.e., dime, quarter, etc.) before cutting. Following inspection of each item, the item was removed from sight and subjects were asked to cut a two-dimensional figure the same size and shape as the item just handled. This task was designated "trial 2." Trial 1 and 2 measurements should address the degree of variation produced by a group of individuals attempting to produce artifacts of a standardized size and shape.

Finally, to address variation produced by one person during a repetitive activity, two subjects (one female, A, and one male, B) were asked to cut from a blank sheet of paper 20 objects the size of a quarter, 20 the size of a 3.5″ floppy disk, and 20 the size of a business card. (Only 3 shapes were selected for this task to avoid potential boredom and hence inaccuracy; cutting 20 objects typically took 20–30 minutes.) Following the cutting of each object, subjects were allowed to compare the resulting cutout with an actual object, which had been kept out of view. Subjects were asked to perform the task once or twice prior to commencement of the experiment and were therefore familiar and comfortable with the process. This experiment was referred to as "trial 3."

The resulting cutouts were measured to the nearest 0.1 mm for various length attributes with digital calipers. For round ones, only diameter was measured. Because most cutouts were not perfectly round, diameter was calculated by averaging maximum and minimum diameter. For square 3.5" floppy-disk cutouts,[2] side and diagonal measurements were calculated by averaging the two side measurements for the former and the two diagonal axes for the latter. For all rectangular items (i.e., business card, dollar bill, and CD case) length, width, and diagonal length were measured. Length was considered the longer of the two major axes, width the shorter, and each was measured at the midpoint along the respective axis. Diagonal measurements were calculated by averaging the two diagonal axes of the cutout. Similar measurements for dimes, quarters, business cards, 3.5" floppies, and CD cases were also made to the nearest 0.1 mm using the same calipers.

Data resulting from the three trials were calculated for coefficient of variation, defined as sample standard deviation/sample mean and expressed as a percentage (i.e., multiplied by 100). Because mean and standard deviation tend to covary, the dimensionless coefficient of variation gives a relative measure of dispersion or variation. For this reason it is superior to other measures of dispersion, particularly when comparing samples with unequal means (Eerkens and Bettinger n.d.).

RESULTS

Table 1 presents coefficients of variation, expressed as percentages, for the cutouts produced by subjects and for a sample of 25 actual items. Not surprisingly, artifacts produced by machine are much less variable than the cutouts produced by human subjects. The coefficients of variation for machine-produced items are well over an order of magnitude smaller than even the smallest one for the human-manufactured items. Statistical comparison using the D'AD test (see Feltz and Miller 1996) of machine-produced and trial-2 human-produced coefficients of variation yield highly significant differences; in all seven cases $p < .000000$. The machines used to produce these items are clearly far more accurate and consistent than humans.

The subjects showed much improvement from trial 1 to trial 2. With the exception of business-card widths, every calculated coefficient from trial 2 is lower than the one from trial 1. In fact, of the 390 paired sets of cutouts (i.e., one from trial 1 and one from trial 2; 30 subjects times 13 measured attributes), 65% are closer to the actual size in trial 2. This suggests that variation or error in memory of size increases with the length of time since the object was initially viewed. In only two cases, quarter diameter and dollar width, do less than half the cutouts show an improvement from trial 1 to trial 2. Similarly, Moyer et al. (1978), Palmer (1988), and Pelli and Farell (1992) found that memory of size and shape is more accurate when subjects are asked to recall these attributes soon after initial viewing. This result confirms that specialists working with standard-sized objects on a day-to-day basis have more accurate mental images of the correct size and shape for a particular object than people who only occasionally handle and produce such objects.

A comparison of coefficients of variation by sex shows little difference. In general, women were slightly more consistent and accurate than men, particularly in cutting figures the size of floppy disks and CD cases. However, the D'AD tests do not show these differences to be significant; in all cases $p > .05$. In addition, women tended to improve from trial 1 to trial 2 slightly more often than men (67% vs. 61%, $n = 221$ and 169 respectively). However, this difference is again insignificant by the chi-square test ($p > .05$). Table 2 breaks down the rate of improvement by sex and by cutout shape and attribute. Whereas some studies of manual dexterity have suggested that women excel over men (e.g., Kimura 1993), others (e.g., Peters and Campagnaro 1996) that control for differences in the size of hands and fingers between

TABLE 1

Coefficient of Variation Values (Standard Deviation/Mean) Expressed as Percentages for Human-Produced Cutouts, Grouped by Sex and Trial, and Machine-Produced Items

	Total	Trial 1	Trial 2	Women	Men	Women Trial 2	Men Trial 2	Machine-Produced
Dime diameter	8.7	8.7	7.5	8.8	8.8	6.5	8.8	.20
Quarter diameter	8.5	9.4	7.4	8.3	8.9	7.2	7.9	.13
Card length	6.7	7.0	4.1	6.9	6.6	4.4	3.6	.05
Card width	8.0	7.1	8.0	7.9	8.3	6.2	9.9	.04
Card diagonal	6.3	6.3	4.4	6.5	6.1	4.5	4.0	.04
Disk side	7.4	9.6	4.3	5.6	8.9	3.3	5.0	.08
Disk diagonal	7.7	9.9	4.6	5.8	9.1	3.4	5.3	.06
Dollar length	5.9	6.7	4.9	5.6	6.3	4.8	5.1	.08
Dollar width	6.5	6.8	6.3	6.5	6.5	6.7	5.9	.07
Dollar diagonal	5.3	5.9	4.6	4.9	5.8	4.4	5.0	.05
CD length	6.9	7.9	4.7	6.2	7.6	4.8	4.6	.10
CD width	6.6	7.8	5.2	5.5	7.6	4.0	6.4	.09
CD diagonal	6.1	7.1	4.5	4.7	7.4	4.1	4.9	.08

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[2] During the course of the experiment, it was discovered that 3.5" disks are not actually square. The two main axes differing in length by approximately 4%. Though detectable, this difference is quite small and approaches the just-noticeable-difference of 3% for human visual perception. For the purposes of the experiment, 3.5" disks were treated as if square.

TABLE 2
Actual Size, Percentage of Cutouts Improved from Trial 1 to Trial 2 as a Total (and by Sex), Percentage of Total Cutouts Underestimated, and Average Deviation from Actual Size (Percentage) for Cutouts Produced

	Actual Size (mm)	% Improved Total (m/f)	% Underestimated Total	Average Deviation from Actual (%)
Dime diameter	17.91	80 (77/82)	77	8.4
Quarter diameter	24.26	47 (46/47)	28	7.9
Card length	88.80	77 (62/88)	84	6.8
Card width	50.93	73 (69/76)	55	6.1
Card diagonal	102.37	87 (77/94)	73	5.9
Disk side	91.95	60 (46/71)	45	5.3
Disk diagonal	128.31	57 (38/71)	40	5.6
Dollar length	156.0	60 (62/59)	72	5.3
Dollar width	64.57	47 (38/53)	28	6.2
Dollar diagonal	169.05	60 (54/65)	69	4.7
CD length	142.34	70 (85/59)	55	5.1
CD width	124.30	60 (62/59)	37	6.5
CD diagonal	189.0	63 (77/53)	48	4.5

sexes have found no difference by sex. The current study lends support to the latter.

Variation in diameter measurements of the small, round objects tended to be higher than in the measurements of the square and rectangular objects (except business-card width). This is likely related to the motor skill of subjects in using scissors for the cutting of smaller objects, where control is more difficult. Thus it is possible that in prehistoric contexts smaller artifacts and attributes may display slightly elevated coefficients of variation due to the greater motor skill they require. Interesting in this regard is that subjects tended to underestimate the size of dimes (77% of dime cutouts; see table 2) while overestimating the size of quarters (72% of quarter cutouts). Knowing that dimes are smaller than quarters, subjects may have been trying to distinguish the two by making one too small and the other too large. The same is not, however, true of length and width measurements among rectangular objects, where the larger length measurements were not, in general, overestimated more often than the shorter width measurements. At the same time, width (i.e., shorter) measurements among rectangular objects, particularly business cards, tended to be more variable (table 1) and to deviate more from actual object size (table 2) than length or diagonal measurements. This suggests that individuals may be more familiar with the larger or maximum length dimensions of common objects and may use this measurement to estimate the size of the shorter attributes such as width. This finding was not, however, confirmed in trial 3, where width tended to be slightly less variable than length.

Table 3 presents coefficient of variation values for the final experiment, trial 3. Not surprisingly, the values for this experiment were lower than for trials 1 and 2; a single individual, with a single mental template, is likely to be more consistent from cutout to cutout than multiple individuals with slightly different mental templates. Values for this experiment ranged from 2.5% to 3.5%. When compared by the D'AD test with cutouts produced in trial 2, as above, many coefficient values from trial 3 were significantly lower ($p < .05$). There was no apparent improvement in accuracy during the course of the 20 cutouts; that is, deviation from actual size did not significantly change from cutout #1 to #20.

DISCUSSION AND CONCLUSIONS

One of the main goals of this study was to determine the minimum variation attainable in producing artifacts by hand from a mental template. Elsewhere Eerkens and Bettinger (n.d.) have used the Weber fraction to derive the minimum coefficient of variation for length perception and estimation. This coefficient, at 1.7%, describes the limit of human visual perception in differentiating the length of an object. However, deficient motor skills and faulty memory serve to increase coefficients of variation above this visual limit. The question, then, is how much error these sources add—how accurate humans can be.

Clearly, technological systems will play a role. Some

TABLE 3
Coefficient of Variation Values for Cutouts Produced in Trial 3 by Individuals for 20 Quarters, 20 Disks, and 20 Business Cards

	Subject A	Subject B
Quarter diameter	3.3	3.0
3.5″ disk side	2.7	3.4
3.5″ disk diagonal	2.6	3.1
Card length	3.5	3.0
Card width	3.2	2.8
Card diagonal	2.8	2.5

technologies, such as pottery production by coiling, are more amenable to adjustment and error minimization than others, such as flintknapping, where the only method of adjustment is further reduction. Technology, then, will affect the ability to control the medium and, hence, overall error. Relative to most prehistoric technologies, we consider scissors and cutting to be fairly accurate and probably on the low end of increased error.

The results of the study, particularly trial 3, indicate that on an individual level coefficients of variation in the range of 2.5–3.0% are *close* to the minimum level of error attainable by humans. The results of trials 1 and 2 suggest that at the group level this value increases to 4.0–5.0%. "Close" is emphasized because the actual minimum may be slightly lower for three main reasons. First, our subjects were not specialists in using scissors; under some conditions prehistoric artisans may have been more familiar with their raw material and craft tools and may have had better control. Scissors are, however, quite precise instruments when compared with, for example, the hammerstones used to remove flakes from a core. Second, although all our subjects were familiar with the general size and shape of the items they were asked to produce, some prehistoric contexts, such as production by craft specialists, may have been characterized by more accurate mental images of the objects being produced. Indeed, other studies (e.g., Algom 1992, Engelhorn 1997, Lachnit and Wolfgang 1990, Pelli and Farell 1992) demonstrate that training and repetition can improve both memory and motor skill. Finally, artisans are probably more motivated than our subjects to produce goods of the exact size and shape necessary for proper functioning or desired by consumers. Thus, the coefficients of variation reported here may be slightly inflated over the minimum attainable value and artifacts produced by craft specialists may be slightly more standardized. For example, Longacre (1999) reports coefficients of variation for vessel height and diameter in the range of 2.0–4.0% for most attributes of pots made by highly specialized potters, slightly less than those obtained in trial 3. Together, this paper and Longacre's study suggest that deficient motor skill and faulty memory combine to contribute an additional 0.5–2% over the Weber fraction to the coefficient of variation for individuals and 2.3–4% for groups of individuals.

By now it should be clear that the adage "practice makes perfect" is an overstatement. Practice can certainly make "closer to perfect" (perfection itself being a relative notion), but given the limits inherent in visual perception, motor skills, and memory, no amount of practice can result in perfection. This study suggests that coefficients of variation in the range of 3 ± 1% are about as perfect as humans can get under most preindustrial conditions. A uniform population of numbers with a coefficient of variation of 3% contains all of its sample within 5% of the mean.[3] Thus, "perfection" for manual production can be interpreted as being within approximately 5% of the intended size.

The values reported here provide a comparative guideline for future standardization studies—a number against which coefficients of variation in other data sets can be compared. For most prehistoric contexts archaeologists will be working with assemblages produced by multiple individuals. In this case, coefficients of variation in the range of 4–5% should be considered close to the limit of human ability to standardize manually produced artifacts. In contexts where the archaeologist can be fairly confident that only one or very few individuals were responsible for making the artifacts this limit can be lowered to a coefficient of variation of 2–3%. Values below these levels likely indicate situations in which prehistoric craft workers were not constructing goods from memory but using independent rulers, scales, or machines. Values greatly exceeding this level may indicate either mixing of artifact types that should be considered separate (e.g., Longacre, Kvamme, and Kobayashi 1988) or greater tolerance for deviation from the "ideal" shape and size.

One of the limitations of this study is that it fails to account for technological system. While the values presented here provide some guidance, it is unclear how much error different systems will add to the baseline Weber fraction and values discussed above. From Longacre's (1999) study it appears that pottery production is roughly as or slightly less susceptible to error than cutting with scissors. In contrast, values for highly standardized stone tools are five to ten times as high as those obtained in trial 3 here (Eerkens 1997, Torrence 1986), suggesting much higher error rates for flintknapping. A valuable future contribution to standardization research would be an attempt to document coefficients of variation for goods produced by specialists under a number of different technological systems.

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[3] Similarly, a normal population with a coefficient of variation of 3.0% contains most (95.5%) of its sample within 6%, or two standard deviations, of the mean (and 90% within 5% of the mean).

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Regions Based on Social Structure: A Reconsideration (or Apologia for Diffusionism)[1]

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Burton et al. (1996) propose a new regionalization of the world based on social structure and display its main features in their figures 2, 3, and 13. Our attention was immediately attracted by the left side of figure 13, which contains three regions—Middle Old World, Canada-West, and Eurasian-Circumpolar. Most of the ethnic groups populating these three regions belong to three linguistic macrofamilies: Nostratic,[2] Afrasian (Semito-Hamitic) (Illich-Svitych 1971–84, 1989; Dolgopolsky 1964, 1989, 1995), and Sino-Caucasian[3] (Starostin 1982, 1984, 1989). As has recently been shown, these three macrofamilies belong to a single megafamily (Starostin

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[2] Substantial evidence linking the six linguistic families of the Old World—Indo-European, Uralian, Altaic, Dravidian, Kartvelian, and Semito-Hamitic (Afrasian) in terms of a single proto-language, Nostratic, was presented for the first time by the Russian linguist Illich-Svitych (1971–84). The historiography of the Nostratic problem is treated extensively in Manaster Ramer (1993). At present Afrasian is treated as a separate unit at the same taxonomic level as Nostratic and related to the latter (Orel 1995*a*, *b*; S. A. Starostin, personal communication, 1999).

[3] The Sino-Caucasian macrofamily, whose existence was demonstrated by Starostin (1984), consists of North Caucasian, Yenisseian (Ketan), Sino-Tibetan, and Na-Dene. Languages belonging to the North Caucasian family are Abkhaz, Abaza, Ubykh, Adyghe, Kabardian, Batsbi, Chechen, Ingush, Andi, Botlikh, Godoberi, Karata, Akhvakh, Bagvalal, Tindi, Chamalal, Avar, Tsezi, Ginukh, Khvarshi, Inkhokvari, Bezhta, Gunzib, Lak, Dargwa, Lezghi, Tabasaran, Agul, Rutul, Tsakhur, Kryz, Budukh, Archi, Udi, and Khinalug (see, e.g., Nikolaev and Starostin 1994:8–14). The Yenisseian family includes at least two well-described languages, Ketan and Kottan, the latter spoken in the 19th century in the Middle Yenissei Basin (Siberia).