STONE TOOL ANALYSIS USING DIGITIZED IMAGES: EXAMPLES FROM THE LOWER AND MIDDLE PALEOLITHIC

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ABSTRACT

Image digitization technology is rapidly becoming more accessible to archaeologists. In addition to including images in artifact databases, digitized artifacts present a number of possibilities for improving stone tool analysis. An overview of some of the issues faced when digitizing artifacts for analysis is presented here followed by two examples of its application to stone tools. The examples deal with problems of direct relevance to Lower and Middle Paleolithic industries of Western Europe, but the techniques and approaches described are generally applicable to many types of stone tool analysis.

INTRODUCTION

The metrical study of lithic variability has not witnessed any major advances in methodology since prehistorians began arming themselves with scales and calipers many decades ago. There are, however, a number of lithic attributes that are difficult to quantify with traditional measurement techniques. Some obvious examples include edge shape, the placement and intensity of retouch, edge symmetry, placement and percentage of cortex, and overall morphology or shape of an artifact. The latter is a particularly good example since it forms the basis of so many lithic typologies, yet it is extremely difficult to quantify. Rather than treat it as a whole, lithic analysts have been forced to reduce shape to a series of linear measurements and calculated ratios. In the case of cortex, its complete presence or absence is relatively easy to note and this kind of observation is usually sufficient to determine primary versus tertiary stages of core reduction. However, amounts of cortex falling between these extremes can be quite difficult to objectively and accurately quantify.

Image digitization, whereby an image of an artifact is transferred to a computer for analysis, is a useful alternative technique that may help address a number of issues in stone tool analysis (Gero and Mazzullo 1984; Dibble and McPherron 1988; Lieberman et al. 1990; Wynn and Tierson 1990; McPherron 1991; Rees et al. 1991). The purpose in this article is to summarize some of the issues confronted with digitization and to present two examples of its application to stone tools. While these examples deal with problems of direct relevance to Lower and Middle Paleolithic industries of Western Europe, the techniques and approaches described are generally applicable to many types of stone tool analysis.

OVERVIEW OF DIGITIZING METHODS

There are three widely available methods for obtaining a digitized image of an object: flat-bed scanners, digital cameras and digitizing tablets. Each method has advantages and disadvantages compared to the others. Scanners, for instance,

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work best with flat objects such as artifact photographs and drawings, but are not well suited for three-dimensional objects. The same could be said for digitizing tablets, though some three-dimensional tablets now exist. Digitizing tablets, on the other hand, can be quite slow. Digital cameras are much better with three dimensional objects and are quite fast, but they produce fairly low resolution images which, in some instances, may not retain enough of the object's detail for analysis.

Costs of these methods are also quite variable though, as with any computer technology, costs continue to decrease. Relatively speaking, flatbed scanners are far and away the least expensive method for obtaining digital images. Digitizing tablets and digital cameras are more expensive depending on the quality and, in the case of digitizing tablets, the size of the unit. Digital cameras constitute an area in which the technology seems to be changing quite rapidly, with image quality constantly improving for a given price. We have tried a number of these units and have generally found that cameras in the upper end of the consumer range or the lower end of the professional range have the features and quality needed for artifact photography.

In the studies presented here, both a digitizing tablet and a digital camera were used. The former is well suited for the first example in which actual and schematic outlines of bifaces were traced from Bordes' (1961) Lower and Middle Paleolithic stone tool typology (cf. Wynn and Tierson 1990; Saragusti and Sharon 1998). In the second example, a digital camera was used to capture images of actual Mousterian tools. The digital camera was selected in preference to a scanner for several reasons: a) it can handle three-dimensional objects as easily as two-dimensional ones; b) the digitization process is virtually instanta-

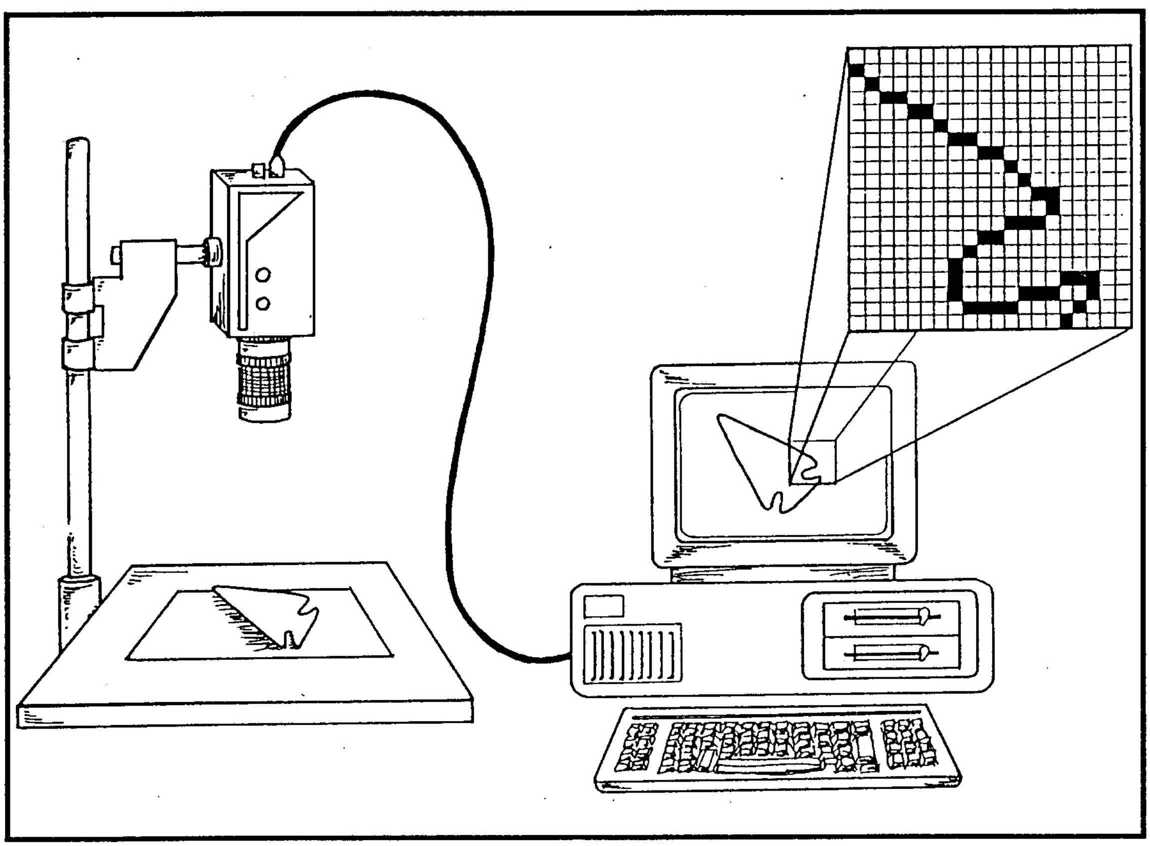

Figure 1. The setup used for digitizing artifact images. The video camera sends an RGB image to a frame-grabber or digitizing board in the computer. Alternatively, a digital camera with built-in memory and digitizing capabilities can now send a digital image to a computer.

neous (1/30th of a second); c) zoom, lighting, color balance and contrast can be adjusted interactively to achieve the best result; and d) the resulting image is easier to work with, because the low resolution makes its size quite small.

The digital camera configuration used to obtain the data presented here is illustrated in Figure 1. A digital camera (JVC TK-870U) with a zoom lens (Fujinon TV zoom lens) is mounted on a camera stand. The live video image is fed from this camera to a digitizing board or frame grabber (an AT&T Targa-16 card installed in the PC), which then directs the image to a video monitor. When the desired scale, focus, lighting, etc. are achieved, software directs the board to capture a frame from the live image and instantly convert it into a still image. At this point, the image can be saved on the computer's hard-disk or processed immediately (see Booth et al., 1992, or McPherron and Dibble, 1987, for more hardware specifics). More recently, we have switched to using digital cameras that integrate the camera with the digitizing board into one hand-held unit. Most of these cameras have built-in preview screens that indicate fairly well how the final digitized image will appear. We consider this an essential feature for these cameras unless the image can be quickly transferred from the camera's memory to a personal computer and viewed there. Transfer time is an area in which digital cameras vary quite a bit but are steadily improving. The latest cameras, while not as fast as the Targa system described here, are sufficiently fast to process hundreds of images in a day.

The hardware, of course, is only part of the technological puzzle. The other is the software used to process the digitized images. There are now a number of commercially available software products to control digitizing boards and to perform certain basic image processing tasks (cf. Rovner 1995); however, we chose to develop our own software to meet our specific needs. Rather than discuss the details of this software, we will focus on several key issues that must be addressed by any image processing program used for artifact analysis.

The first of these is distortion. While digital cameras offer certain distinct advantages for this type of work, the camera and lens can produce significant distortions in the digitized image. The effect of lens distortion is easily demonstrated by digitizing a section of square grid paper with a camera and superimposing the resulting image over the original grid pattern (Figure 2). In each corner of the digitized image, lines which should remain parallel tend to bend either towards or away from the center of the image. The center remains largely unaffected by this type of distortion.

There are a number of ways to address lens distortion in digitized images. One can, for instance, mark a number of control points with known coordinates on the original image. By comparing the coordinates of the digitized control points to their true coordinates, formulas can be derived to shift each pixel in the digitized image to remove the distortion. In GIS this process is called rubber-sheeting, and it is used to remove distortion from aerial photographs. It is, however, a time consuming and difficult process. In our case we estimated that this type of lens distortion was not a significant issue, because only the edges of the screen are severely affected and the stone tools to be studied were arranged in the center of the screen.

The digitizing camera may also distort the image by changing its aspect ratio. The aspect ratio describes the width of each pixel in the image relative to its height. To make accurate measurements from an image, the width of each pixel should equal its height, for an aspect ratio of 1. The camera used in our study, however, produces pixels whose heights are considerably larger than their widths (see Figure 2). As a result, 10 pixels might represent 10 mm along the horizontal axis and 14 mm along the vertical axis. Tests on other digital cameras produced the same kinds of problems, though to different degrees and even in different directions (Table 1). By way of comparison, we also tested a flatbed scanner. We found no noticeable bending distortion, as described above, and the aspect ratio was perfect. This was true even when we used xeroxed originals that had been enlarged or shrunk. Thus for two-dimensional objects, scanners are the best method for acquiring digital images.

Unlike lens distortion, the aspect ratio affects the entire image equally. As a result, once the aspect ratio error is known, it can be easily corrected by either compressing or expanding the image along one axis. The challenge is to determine both the aspect ratio and the scale for each

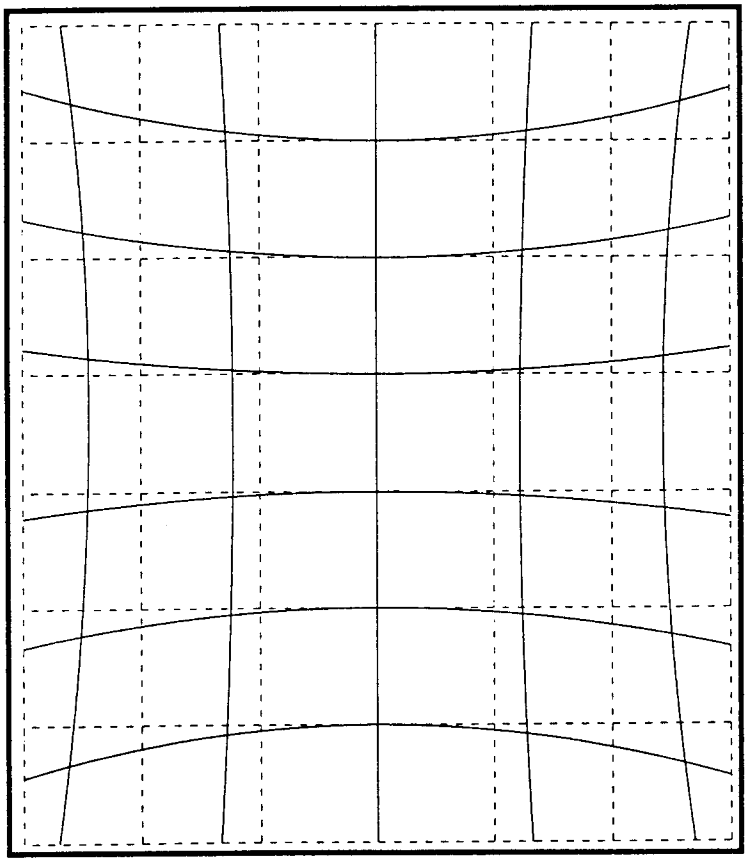

Figure 2. A schematic image of a regular, square grid digitized with a digital camera. Note the rectangular shape of the grid cells and the bending of the grid lines in the corners (the dashed lines are straight lines superimposed on this image for comparison). Depending on the lens, the bending can be in the opposite direction and the grid cells can be stretched horizontally rather than vertically.

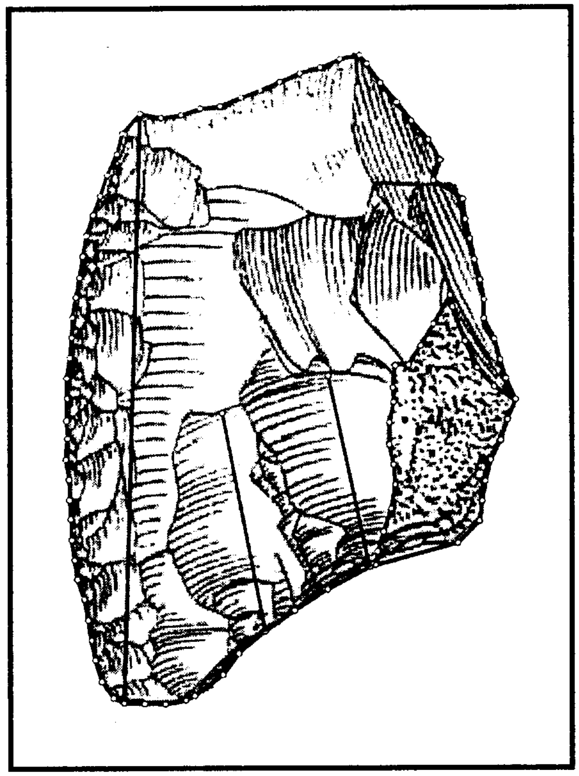

Figure 3. An example of a digitized artifact drawing with measurements. The points around the edge are taken at a fixed interval to give an artifact outline. Next, lines can be drawn to note certain features -- for instance, from left to right, the extent of retouch, the orientation of flake removals, and the area covered in cortex.

Table 1. A comparison of distortion in digitized images from several different cameras and a flatbed scanner.

Camera Model	Aspect Ratio (width x height)
JVC Camera and Targa Frame Grabber	92:100
Ricoh RDC-2	97:100
Kodak DC-40	98:100
Sony Mavica MVC-FD7	100:103
HP Scanjet IIcx	100:100

digitized image. One way to accomplish this is to digitize a circle of known diameter immediately before digitizing an artifact image. The software can then analyze the digitized image of the circle to determine its width and height, which, of course, should be an equal number of pixels. Based on this information, the program calculates the aspect ratio and the scale, represented as the number of pixels per centimeter. In our case, the camera consistently stretched the image along the vertical axis. Rather than stretching the image a corresponding amount along the horizontal axis, which would require extrapolating pixels, the vertical aspect of the image was reduced by periodically dropping an entire row of pixels from the image. This technique completely corrects the aspect ratio error, is very simple to program, and can be applied to each image in less than a second.

Before proceeding to the examples, a word about calculating the scale for a two-dimensional image taken from a three-dimensional object is appropriate. With a three-dimensional object, the region of the artifact nearest the camera lens has a scale different from that of the region furthest from the lens. Furthermore, with the circle scale technique, the scale is easily recorded at either the top or the bottom of the artifact but not anywhere in between. On relatively flat stone tools, such as flakes and blades, differences in scale from the top to the bottom are not noticeable. On thicker objects, such as Acheulian bifaces, differences are much more significant. We have considered solutions to this problem, but for the moment we have chosen to sidestep it by analyzing shape independently of size on largely three-dimensional objects.

Once the artifact image is digitized and its scale calculated, the first step in the analysis is to outline the artifact (Figure 3). This is accomplished by sampling the edge at a fixed vertical and horizontal interval (see Gero and Mazzullo 1984:320; Goodson 1989; Lewis and Goodson 1991). These points provide a context for the measurements that follow. Next, the location or orientation of certain kinds of artifact features such as points, lines and polygons can be recorded on the digitized image (see Figure 3). To accomplish this, the program allows us to trace lines on top of the image and to store these lines as a series of end-points with an associated variable name. With these data -- the outline of the artifact and the traced lines -- the software can automatically make certain kinds of measurements and return a single value as the result. For instance, the program can automatically calculate the box width or length (height) of an artifact by analyzing the range of the outline points. The surface area of the artifact can also be easily calculated with the outline points. Similarly, in a two-step process, by tracing a region of the artifact (the cortex, for instance) the program can automatically calculate the surface area of just that region and compare it to the entire artifact to compute a percentage (see Rovner 1995).

EXAMPLES

Two examples of image digitization applied to stone tool analysis follow. In the first example, biface outlines from Bordes' (1961) typology for the Lower and Middle Paleolithic are digitized and the shapes analyzed to determine a method for automatically orienting bifaces in a standardized, completely objective manner prior to making other kinds of observations on their shape. Using Bordes' drawings allows the results of each quantitative method to be evaluated against the standard for the typology. In the second example, the placement of retouch on a set of Middle Paleolithic scrapers from the site of Biache-St.-Vaast (Tuffreau and Sommé 1988) is examined after the artifacts have been automatically oriented. Here image digitization provides an entirely new data set to address the issue of tool reduction.

Example 1 - Biface Orientation

The traditional approach to describing and analyzing Acheulian biface morphology has relied on a relatively small set of caliper measurements. Yet through the years, the number of measurements used to quantify biface shape has steadily increased as researchers have become dissatisfied with previous results. Bordes (1961), for instance, incorporated length, width in two places, thickness, and the position of the maximum width along the length axis. Roe (1968, 1981) added another width measurement and two additional measurements of thickness. In both cases, the measurements were designed to quantify those aspects of biface morphology best described as edge shape, elongation and refinement. Of these three, edge shape is the most difficult to represent from a small set of caliper measurements,yet it is the aspect of biface morphology that has probably received the most attention.

For this reason, Wynn and Tierson's (1990) study of biface morphology is interesting. Instead of imposing their own notion of which aspects of variability in edge shape are statistically important, they chose to describe edge shape as accurately as possible and to isolate statistically the portions of the edge that varied significantly among biface collections from different regions. The method they used to describe edge shape is best described as radial. It involves tracing the biface edge onto a sheet of paper, locating the center of the biface, and then drawing a series of 22 lines from the center to the edge at specified intervals. The lengths of these lines describe the shape of the biface edge and are amenable to statistical analysis. This approach to digitization has been used in other studies of Paleolithic artifact morphology (Montet-White 1973; Gero and Mazzullo 1984; cf. Dibble and Chase 1981).

This method has the advantage of avoiding subjective, a priori determinations of "important" aspects of edge shape, and it can be almost completely automated using the digitizing technology just described. As a result, thousands of bifaces could be studied in great detail very quickly and efficiently. Yet, there is one caveat. Before the biface can be digitized and its edge shape quantified, it must be placed in a standard orientation. However, bifaces do not have any reliable landmarks that can be used to orient them in a consistent manner, unlike the platform or point of percussion that is often used in the analysis of flakes and flake tools. As a result, the standard orientation is on the basis of shape, the very aspect of biface variability that is being measured. Since the focus in biface shape analysis has always been the point or tip, the standard orientation is with the point up, the base down, and the edges out. Unfortunately, this simple description of the standard still leaves open quite a large degree of variability in orientation, particularly when the biface is fairly asymmetrical. In some instances it is not even clear which end is best defined as the tip, particularly when the maximum width and thickness do not occur at the same end.

So to extend Wynn and Tierson's study a step further and arrive at a completely automated and objective technique for examining biface morphology, a quantitative method for arriving at a standard orientation is required. To this end, each of the outline drawings in Bordes' (1961) publication of the biface typology were digitized and their symmetry mathematically analyzed and compared to Bordes' original orientations. The bifaces in this publication were selected for two reasons. First, they are intended to represent the full range of shapes that one might encounter when studying a biface assemblage. Second, Bordes' publication is considered the standard. A new method for achieving standard orientations can be judged successful, and will more likely be accepted by the archaeological community, if it comes closest to matching Bordes' results. For the purposes of this study, therefore, it was assumed that the bifaces in Bordes' publication were correctly oriented on the page.

Each biface outline was digitized with the edge of the page parallel to the Y-axis. A computer program then applied several different orientation algorithms to the digitized points representing the biface outline, each of which resulted in a new orientation. The angle of rotation from the original orientation to the new computed orientation is thus a measure of the magnitude of difference between Bordes' method and each computed method.

One method of orientation is based on the longest line through the edge contour of the biface (Figure 4a). This method involves very few calculations and is, therefore, quite fast. It is also the easiest way to orient a biface by hand with only a pair of calipers. However, it fails to replicate Bordes' orientations, most noticeably with triangular and subtriangular bifaces (see Debénath and Dibble, 1994, for definitions of these biface types), since the longest line through these forms runs from the tip to either of the two corners at the base (Table 2).

A second method corrects this problem by selecting the longest line through the center of the biface (Figure 4b). While the center of the biface is difficult to locate reliably by eye, it is easily computed in digitized form as the average of each edge point. The center point along the X axis is the sum of all X coordinates divided by the number of coordinates, and the center point along the Y axis is the sum of the Y coordinates divided by the same number. This method succeeds far better than the first method in replicating Bordes' original orientations (Table 3). Triangular bifaces are now

Table 2. Angle differences (in degrees) using the longest line method of rotation

	Triangular	Sub-Triangular	Cordiform	Ovate
Minimum	2.00	1.00	0.00	1.00
Maximum	16.00	8.30	15.00	40.00
Median	9.50	21.50	5.00	4.00
Mean	9.13	26.75	6.54	8.60
N	8	4	13	10

Table 3. Angle differences (in degrees) using the centered longest line method of rotation

	Triangular	Sub-Triangular	Cordiform	Ovate
Minimum	0.00	1.00	0.00	0.00
Maximum	3.00	76.00	14.00	17.00
Median	2.00	7.00	4.00	2.50
Mean	1.75	22.75	5.00	4.00
N	8	4	13	10

Table 4. Angle differences (in degrees) using the distance to opposite edges symmetry method of rotation

	Triangular	Sub-Triangular	Cordiform	Ovate
Minimum	0.00	0.00	0.00	0.00
Maximum	2.00	4.00	10.00	14.00
Median	1.00	1.00	2.00	2.00
Mean	1.00	1.50	2.61	3.20
N	8	4	13	10

Table 5. Angle differences (in degrees) using Callow's method of rotation

	Triangular	Sub-Triangular	Cordiform	Ovate
Minimum	0.00	0.00	0.00	0.00
Maximum	2.00	6.00	8.00	14.00
Median	0.00	2.00	2.00	2.00
Mean	0.75	2.50	2.92	3.20
N	8	4	13	10

Table 6. Angle differences (in degrees) using principal components analysis

	Triangular	Sub-Triangular	Cordiform	Ovate
Minimum	0.816	3.093	0.225	0.097
Maximum	10.459	4.675	6.089	3.113
Median	2.772	4.294	2.968	1.359
Mean	3.752	4.089	2.802	1.516
N	8	4	13	10

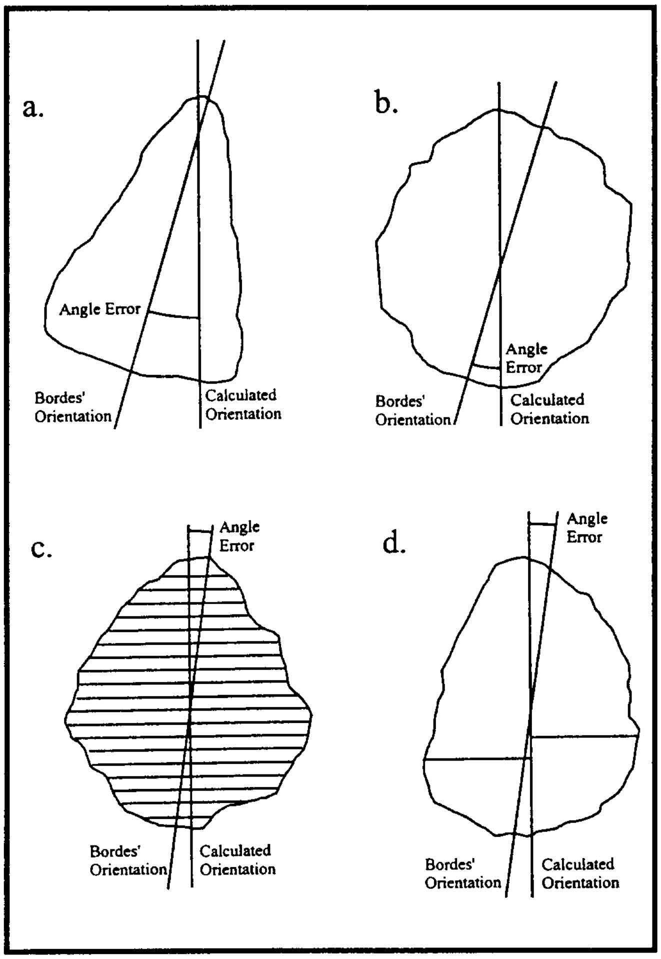

Figure 4. Examples of four of the rotation methods: a) longest line through the biface; b) longest line through the center of the biface; c) a comparison of the distance to opposite edges along a line through the center of the biface; and d) Callow's method, which compares the furthest distance to opposite edges along a line drawn from the tip of the biface. In each example, the biface is displayed in the new or calculated orientation, and Bordes' original orientation is shown with the line that runs diagonally through the artifact. The difference between this line and the line marking the calculated orientation is the error in the rotation method.

more correctly oriented, but bifaces with flattened tips and bases, such as elongated ovates, are still not properly oriented because the longest line through the center is on the diagonal. This method fails in these cases because it focuses only on length and makes no effort to check for symmetry in the edges. The fact that either of the first two methods works at all is explained by the fact that bifaces are generally symmetrical along their long axis.

A third orientation method explicitly includes edge symmetry. Each biface is oriented on a line which passes through the center and divides the edge contour into two symmetrical halves (Figure 4c). The symmetry of the halves is evaluated by measuring the distances from the center line to each edge at a number of intervals along the length at that line. The symmetry is expressed as the sum of the differences in each of these edge measurements. A perfectly symmetrical division of the biface will result in a sum of zero. Since this will seldom be the case, the line of maximum symmetry is the line which results in the lowest sum. Lines yielding a biface orientation with a width greater than the length are discarded in favor of the next best orientation. This method does quite well with all forms and particularly improves the results of subtriangular bifaces (Table 4).

The fourth orientation method is based on a technique described by Callow (1976:3.21) and is very similar to the third method just described. A line of symmetry is drawn from the tip through the biface at such an angle that the longest perpendicular lines from it to each edge are equal in length (Figure 4d). This method differs from the previous one in that here edge symmetry is measured at only one location. Also, rather than using the center of the biface to anchor the line, this method uses the tip. While acknowledging the importance of the tip in any definition of biface orientation, this method has the disadvantage of relying on a landmark that is not always easy to locate objectively and reliably. Moreover, broken tip bifaces cannot be oriented along their line of maximum symmetry without a subjective extrapolation of the missing tip. For the purposes of this study, where Bordes' drawings are being used as the standard against which each method is compared, the topmost point of each biface outline was accepted as the tip. In order to use this fourth method to automatically orient bifaces, an objective method for finding the tip would be necessary. Overall, this method performed as well as the more complicated edge symmetry method previous outlined (Table 5).

Lastly, statistical methods for orienting bifaces were explored, based on the idea that linear regression analysis might be appropriate for this type of problem. In theory, the digitized edge points can be treated as a point scatter suitable for regression analysis. It was expected that regression analysis would place a line of "best-fit" through the point scatter that would closely approximate the axis of maximum symmetry. The advantage of this approach is that it is highly replicable. The technique works reasonably well with some extremely elongated, oval shapes. As soon as the edge shape strays from this idealized form, however, the regression line increasingly fails to match the standard orientation (Figure 5a). Moreover, the results of the regression analysis vary with the original orientation of the biface. A biface lying on its side will produce a different regression line from one standing on end. The reason for this failure lies in the way regression analysis measures the best fit line. It works to minimize the sum of squared vertical distances or horizontal distances between each point and the regression line. Deciding whether to use vertical distances or horizontal distances requires making a decision about the relationships between the two variables.

A better measure of best-fit, which makes no judgements about the relationship between the variables, looks at the shortest distance between each point and the regression line. This line is called the orthogonal regression line (Madsen 1988:11), and is the type of regression used in principle components analysis (PCA). Hence, in the fifth method of orientation tested as part of this study, PCA was performed on the digitized X and Y coordinates of each of Bordes' biface outlines. PCA works by maximizing the variability accounted for by the first component while minimizing the variability around this component. The second component does the same with the remaining variability such that the two components are perpendicular to one another. As the results (Table 6, Figure 5b) indicate, when the biface outline is rotated according to its principal components, the orientation quite closely matches the desired result. PCA is on average nearly as good as the techniques that explicitly measure edge symmetry, and the largest error in this case is lower than in any of the other methods. In other words, this method consistently does well, though on average some of the other techniques perform slightly better.

In summary, as can be seen in Table 7, the two methods that attempt to maximize symmetry of edge shape come closest to replicating the orientation of Bordes' biface drawings. While the median result for the two methods based only on long axes is nearly acceptable, when these methods fail they tend to do so catastrophically. The maximum divergence from Bordes' method is lowest for the PCA method. The PCA, however, was the most difficult to apply. It required exporting the points from the digitization program into a statistics program. The statistically rotated points then had to be exported from the statistics program and imported back into the digitization program. On the other hand, Callow's method was by far the easiest to apply and also performed well. It was no doubt aided by the fact that the tip had already been identified, an advantage that the other methods did not have. Since the other edge symmetry method requires no prior identification of biface landmarks and achieves a result barely distinguishable from Callow's, it appears to be the best choice.

These results confirm the importance of edge symmetry along a long axis in standard biface orientation. They also suggest that a program of measurement and analysis of digitized images could be quite effectively applied to future studies of biface shape. In such a program, a biface would be placed under the camera, digitized, automatically rotated to a standard orientation, and then automatically measured following the methods outlined by Bordes, Roe, Wynn and Tierson, or by some yet-to-be defined method. This program would have the advantage of being able to gather a tremendous amount of detailed and potentially useful data in very little time.

Example 2 - Scraper Retouch

The interpretation of different morphological scraper types remains a significant question in Middle Paleolithic archaeology. Dibble (1995a) suggested that certain of Bordes' (1961) scraper types, notably the single-edged side scrapers, reflect less resharpening and rejuvenation of their edges than other forms, especially the convergent and transverse types. That is, as edges are repeatedly retouched, the morphology of the piece changes and this in turn affects its classification. This interpretation suggests that scraper morphology is best seen as a continuum of variation, which contrasts with a traditional view that it reflects discrete, normative types.

Previous demonstrations of this notion have relied on two major aspects of tool morphology:

Table 7. A comparison of the various methods of biface rotation (angles in degrees)

	Longest Line	Centered Longest Line	Distance to Edge Symmetry	Callow's Method	PCA
Minimum	0.00	0.00	0.00	0.00	0.097
Maximum	76.00	83.00	14.00	14.00	10.459
Median	3.00	5.00	2.00	2.00	2.496
Mean	6.00	10.03	2.29	2.46	2.799
N	35	35	35	35	35

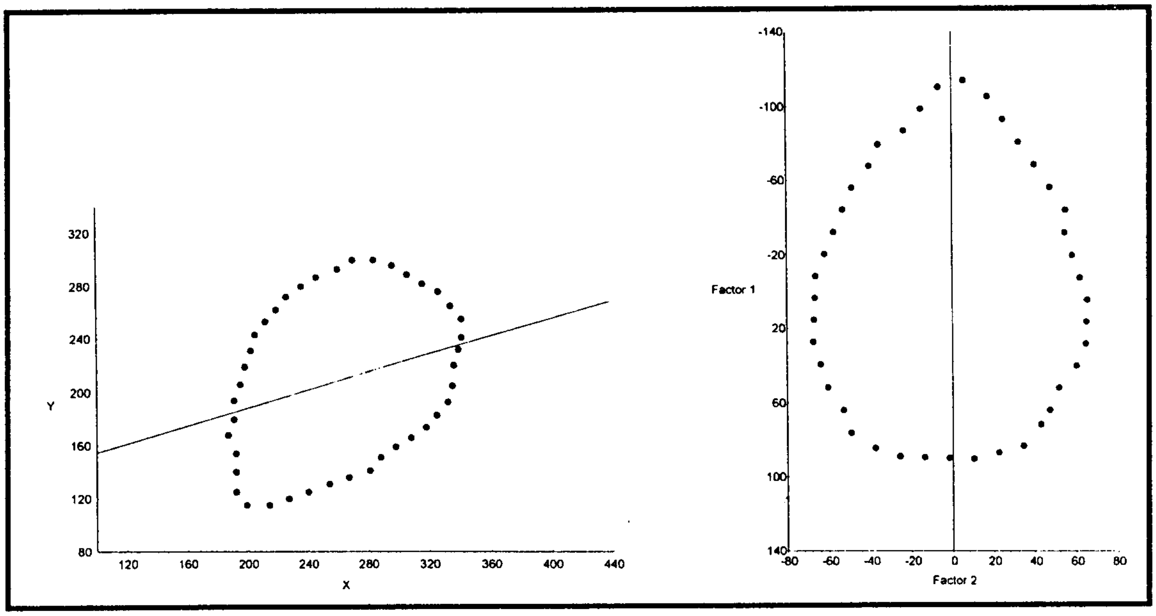

Figure 5. Rotation using statistical methods: a) a regression line through a randomly oriented biface does not provide a good basis for orientation; b) using principal components analysis, the first component rotates the same biface into an orientation that compares very well with Bordes' original.

the dimensions of length, width, and thickness; and a characterization of the intensity of retouch. The approach taken was based on the assumption that a more highly reduced piece would show evidence that it had lost a significant portion of its surface area through retouch and that repeated retouching of an edge would result in heavier retouch. A different approach was attempted here, through the use of image digitization, to determine the proportion of an edge or edges that were retouched and to locate the position of the retouch along the edge(s). The use of image digitization and analysis helped to define and quantify both of these observations, as well as to orient the pieces.

The Middle Paleolithic site of Biache-St.-Vaast (Tuffreau and Sommé 1988) provides suitable material for analyzing some of the dynamics of scraper production through digitization. Most of the assemblages that have been used to test the reduction models have exhibited a relatively high degree of utilization -- ones with many scrapers overall and many of the forms that would reflect the most reduction through resharpening. The choice of such assemblages is necessary because of the need for large sample sizes for each of the type classes, and because sufficient reduction must have taken place in order to have its effects clearly visible. The drawback to these kinds of assemblages is that most of the material is already heavily reduced. Biache, on the other hand, appears to have been a very lightly utilized industry (Dibble 1995b) and has, therefore, more potential to show earlier stages of the reduction process. The types of scrapers represented here are mostly single, double, and convergent forms. All of the complete scrapers from the site (N=97) were digitized for this study.

Because this study dealt with three-dimensional objects, the easiest approach was to use the video camera connected to a computer with a frame-grabber. The artifact was initially positioned beneath the camera and the zoom lens adjusted to size it appropriately. A five centimeter circle scale was then placed on top of the artifact and the image of that was digitized. As discussed above, this served not only to calculate the scale in terms of pixels/centimeters, but it also enabled the program to correct for distortion. The artifact itself was then digitized and a black-and-white image was transferred to the computer monitor.

Percent of Retouch

A more fundamental observation in addressing the question of differential utilization of different artifact classes is based on the percentage of edge that was retouched. If different scrapers reflect differential intensity of use and rejuvenation, this should be reflected in the overall percentage of available edge that was retouched. Also, it would be interesting to cross-check other measures of intensity of utilization (such as retouch intensity) with the overall percent of retouch.

However, because the edges of flake tools are not very straight and are often fairly irregular, an accurate measurement of the length of an edge, retouched or not, is difficult. Also, when looking at how much of a tool's edge is utilized, it is important to consider other characteristics of the edges that might have constrained or prevented their utilization. Among scrapers, for example, thick, blunted cortical edges, called "natural backs," are rarely retouched, probably because it is difficult to achieve a sharp working edge on them. Similarly, and probably for the same reason, flake platforms are seldom retouched into scraper edges. So, in calculating the percentage of edge that was retouched, it would be meaningful to adjust the total edge circumference of a flake blank by subtracting from it such areas that actually constrained retouch. This adjustment would express the length of the retouched edge(s) relative to the total edge that could be potentially utilized. The use of image digitization made this a straightforward process.

The percent of retouch was calculated in four steps:

1. The perimeter of the object was traced automatically by the program and from this the length of the periphery of the entire piece was calculated. The calculation of length was based on the sum of the Euclidean distance between each subsequent pair of x,y points located along the periphery.
2. The location and extent of the platform was noted by clicking on two points along the lateral edges (points A' and A" in Figure 6a). The length of the perimeter represented by this portion was then subtracted from the total periphery length.
3. The location and extent of any naturally-backed areas were similarly noted and subtracted from the periphery length (between points B' and B" in Figure 6a).
4. The location and extent of each occurrence of scraper retouch was similarly marked (points C' and C" in Figure 6a), and the total length of retouched edge was calculated as the sum of these periphery segments.

On the basis of these data, the percent of retouch was calculated by dividing the total length of retouched edge by the total adjusted length of the periphery.

It should be emphasized that this method of calculating this measure is very fast (a few mouse clicks per piece) as well as very accurate (because it takes into account edge curvature instead of being based on a linear estimate).

Location of Retouch

The second variable of interest was the location of retouched areas. To a large extent, scraper typology depends on how many edges have retouch on them: single scrapers have only one lateral retouched edge; both double and convergent scrapers have two lateral retouched edges. It also depends on location in that convergent scrapers have retouched portions that meet at the distal end. But more precise information concerning the location of the retouched portions of edges was necessary for understanding the process of reduction.

Contrasting the two alternative explanations can illustrate why retouch location is important.

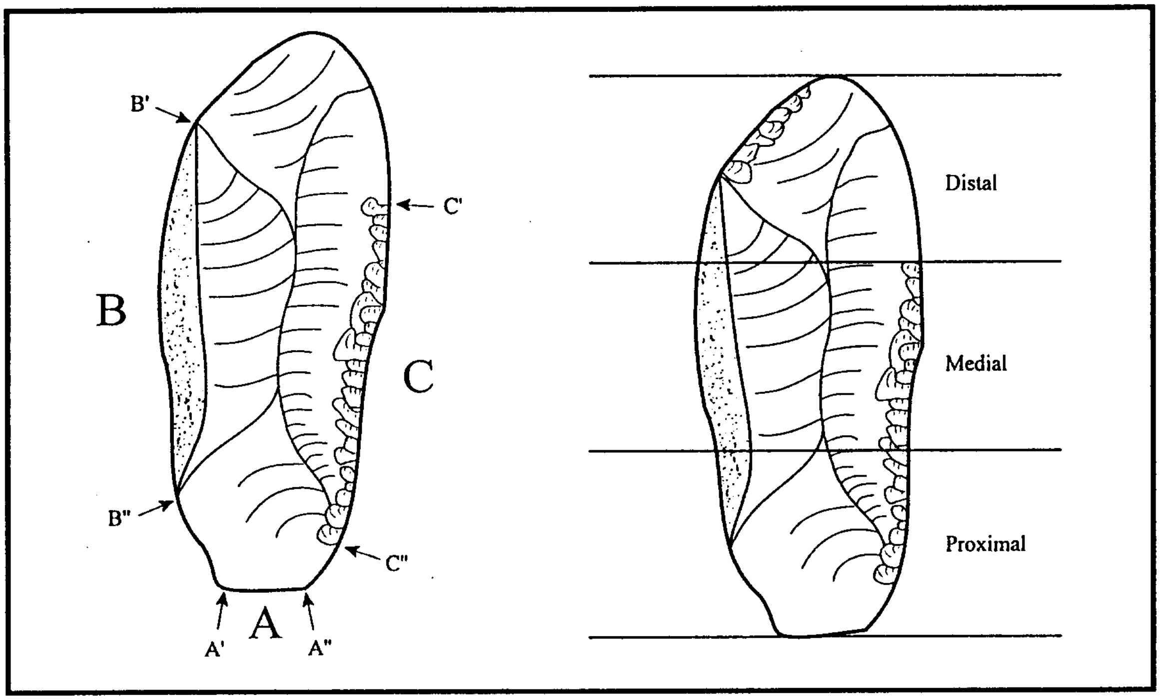

Figure 6. On the left, an example of how the platform (A), naturally backed areas (B), and retouched portions (C) of a scraper were identified. On the right, the scraper is divided into proximal, medial and distal thirds so that the location of retouch can be assessed in each.

If convergent scrapers represent a continuation in the application of retouch, then the location of retouch in the double scrapers should be moving in the same direction; they may have fewer segments retouched, but the retouch on them should be positioned in such a way that it is clear that simply the application of more retouch could have resulted in the typical convergent form. Likewise, the location of retouch of these types should follow a pattern already recognizable in the single scrapers. The important point is that we would expect to see a continuous progression in the location of retouch from the single through the double to the convergent types. On the other hand, such patterns might not be apparent if the types were really distinct from each other. It could be, for example, that most convergent scrapers are retouched only on their distal portions, while double scrapers were usually only retouched proximally. If this were the case, there would be no way to transform such double scrapers into the typical convergent ones simply by adding more retouch to the edges.

To look at retouch location, it was decided to have the program partition each tool into thirds along its length axis (proximal, or near the platform, medial, and distal) and then to note for each edge (right and left) whether or not retouch occurred in each of these areas. There are six edge segments, three on each edge. If an entire edge was retouched, then all three edge segments would be marked as containing retouch. In this case the presence of natural backing is ignored.

There were three steps in determining the location of retouch, after the artifact was digitized.

1. Rather than orienting the scrapers with the platform down and a vertical axis of flaking, as is traditionally done in lithic illustration, each artifact image was rotated by the computer using the second method described above, i.e., based on the longest line that went through the center of the object. This ensured that the partitioning of the edge segments would be comparable among different objects.
2. The artifact was divided automatically by the program into three equal segments perpendicular to the long axis, representing the proximal, medial, and distal thirds of the piece (Figure 6b).

3. For each edge, it was determined whether or not a retouched portion existed in each of the segments. In Figure 6b, for example, the left edge has retouch on the distal third only, while the right edge has retouch in the proximal and medial thirds.

The resulting data set thus consists of six observations: a true/false value of retouch occurring in each of the six segments. While these sorts of observations could have been taken without a digitized image, the results would probably not be as accurate because both the orientation and partitioning of the edges would be more subjective. But of greater significance was the speed of entry: as the endpoints of each edge were located for determining the length, each of the edge segments could also be automatically recorded.

Although the details of this study appear elsewhere (Dibble 1995a), the approach based on image digitization shows the actual process by which retouch was applied to the scrapers much more clearly than does more "traditional" analysis of their dimensions. Figure 7 allows us to examine the location of retouch as it appears on whole tools, considering the condition of both edges simultaneously. For those tools with only one retouched segment, the segment most often retouched is the distal one. For those with two retouched segments, the two segments most frequently occur on the same edge, comprising the distal and medial segments, although a small number also exhibit retouch on the second edge. With three retouched segments, many more tools have retouch on the second edge, though a similar amount continues the retouching on the first edge. With four retouched segments, the second edge must, by definition, contain retouch, and in most cases this is located distally and accompanied by retouch along an entire edge. This trend continues with those with five retouched segments, and with six retouched segments both edges are completely retouched.

Thus, it is clear that the application of retouch to these scrapers follows a regular pattern: it begins at the distal end and moves proximally as

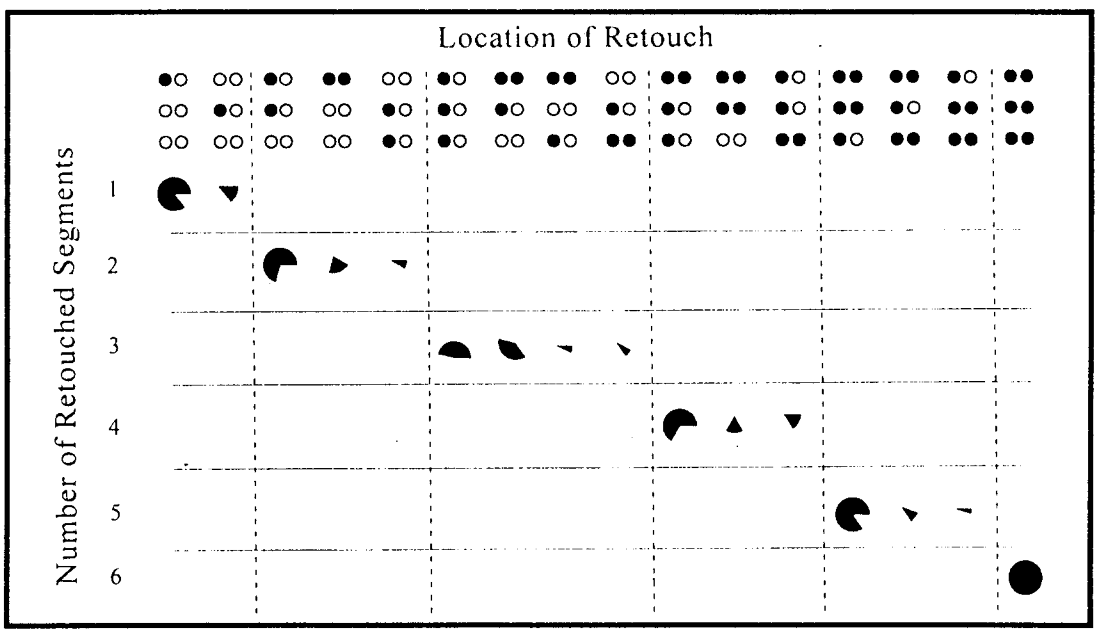

Figure 7. Location of retouch on complete tools. The series of circles at the top of the graph represent the six potentially retouched segments (distal [at top)], medial, and proximal [at bottom], for the two edges). Filled circles represent segments that are retouched. Where only the left or right edge is retouched for a particular segment, the distinction between which side is retouched is ignored. Thus in the first column, all distal third segments, right and left, are combined into one category whereas in the fourth column both the distal left and right edges are retouched so the distinction is retained. For each number of retouched segments, the pie slices represent the proportion of cases with the pattern shown at the top of the graph. (from Dibble 1995a).

retouch increases along one edge. At some point, usually after one edge is retouched on at least two segments, the second edge begins to receive retouch. While neither of these measures would have been impossible to record by more conventional means, the increased accuracy, precision, and reliability afforded through digitization are significant advantages.

CONCLUSIONS

Given the new types of data that result from the analysis of digitized images, there are a number of problems in Old and New World lithic analysis that could be productively addressed using the approach outlined in this paper. However, a number of potential problems exist. Some of these are technical issues that arise from optical peculiarities such as lens distortion, but methodological issues also exist, especially in the definition of the variables that can be acquired through digitization. The examples presented here benefited from having very tightly defined research foci. In the first example, in which an objective method of achieving a standard biface orientation was the goal, the measurements were easily defined as points taken along the outline of the biface edge, but the analysis of these points required the development of several special algorithms that lay outside the range of standard methods of statistical analysis. In the second example, in which quantifying the degree and placement of scraper retouch was the goal, the difficulty lay not in the analysis of the data but in the definition of the measurements.

In terms of its potential for lithic analysis, digitization should be seen not as a replacement for standard caliper measurements but as a new technique for producing data that would otherwise be difficult to gather accurately or reliably. In both of our examples we used digitization to quickly collect detailed data on a relatively restricted sample of tools. In the Biache example, the remainder of the assemblage was also analyzed with more traditional techniques, and the results of the two types of studies were integrated. On the other hand, the long-term goal of the biface study is to automate the measurement of a selected set of variables to the point at which very large samples can be analyzed in much less time than would otherwise be possible.

We would be surprised if digitizing equipment immediately becomes as essential a part of every analyst's tool kit as laptop computers and digital calipers are today. There is still plenty to be learned from traditional techniques of measurement and analysis. We will not be surprised, however, to see many more instances in which digitized images are used to address specific problems in stone tool analysis that until now have been very difficult to approach. As with all computer-based technologies, the impediments, measured either by price or the technical expertise required, are dropping steadily and quickly -- so much so, in fact, that we have avoided mentioning the subject so that this article would not be outdated before it even appears in print. The larger issues, i.e., methodological problems and techniques of analysis will require more discussion in the future as more analysts employ digitization in their studies.

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