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Digital Palaeography and the Old Swedish Script

The Quill Feature Method as a Tool for Scribal Attribution

1 Introduction

The use of computers and digital methods have affected the field of philology in many areas. In textual criticism, computational methods have been employed to investigate the genealogy of manuscripts (e.g. Maas

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Abstract: In this article, the so-called Quill Feature method is tested as a means for scribal attribution in mediaeval manuscripts and placed in a palaeographic context. The Quill Features encompass a range of measurable features such as stroke curvature and variation in the width of strokes that graphs are comprised of, giving consideration to the angle at which they are drawn. The construction of the mediaeval pen, the quill, creates variation in the width of strokes, most importantly due to direction and force of pressure. It has been assumed that individual patterns can be discerned in this variation. The manuscript chosen for investigation is Cod. Ups. C 61, which contains a number of St Birgitta's Revelations and other material connected with this saint. Earlier researchers claimed that three or four scribes produced this manuscript, and this assertion was tested with the Quill Feature method. It transpired that the resultant values, calculated through measuring the investigated features, were very similar for the pages produced by the same scribe, which means that the method identifies important regularities in the scribal hands. Nevertheless, some of the investigated hands showed great similarities and were difficult for the computer to separate. Finally, the strengths and weaknesses of the digital methods of script analysis are discussed. The main advantage of these approaches is that a computer can measure characteristics of the script that cannot be discerned with the naked eye, and with a high degree of exactness. One weakness is that the measurements obtained are given in numbers, and can thus be difficult to apply to the script signs. Furthermore, one single method cannot provide a full description of script characteristics, so a combination of methods, both digital and manual, is desirable.

Key words: Digital palaeography, quill features, Gothic script, image analysis.

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2010), and the electronic text editions of today can benefit from all the possibilities offered by digital text encoding (e.g. Haugen 2008). With the aid of certain applications from HTR (*Handwritten Text Recognition*), such as *Word Spotting*, unedited manuscripts can be searched for word forms (e.g. Wahlberg et al. 2014a). One field that has grown rapidly during the last ten years is that of *digital palaeography*. This is in fact a very broad term that incorporates a large range of digital methods, all of which share the common feature of making use of computers to analyze the physical shape of script signs in a manuscript. Important contributions have been made by such researchers as Arianna Ciula (e.g. 2005), Peter Stokes (e.g. 2007) and Lambert Schomaker (e.g. Bulacu & Schomaker 2007). On Nordic material, however, only few attempts have been made in digital palaeography thus far, even though researchers have highlighted the necessity of such approaches (e.g. Åström 2010). An important task is therefore to test the existing digital tools on Nordic material and subsequently, if necessary, adjust them accordingly.

Although methods differ, digital palaeography variously aims to measure and quantify the physical characteristics of the script signs. In some methods, the aim is to measure the actual form of the graphs (i.e. the category of morphology). One such approach is *System for Palaeographic Inspections* (SPI; see Ciula 2005), where a centroid, i.e. a kind of average of the graphs, is created on the basis of graphs taken from the manuscript under investigation.

This article will focus on a method of digital palaeography often referred to as the Quill Feature method. The basis of this application is the measurement of width of the strokes constituting script signs, with consideration of the direction in which the strokes are drawn. Thus the width of the strokes is correlated to the angle. The medieval pen, the quill, was constructed in such a way as to create variations in width according to the direction in which it was moved, and also according to the amount of pressure force applied (see below). It is this variation that the computer measures and quantifies. The computer registers the features in question in every graph in the same way, irrespective of which graph-type or grapheme it belongs to. The Quill Feature method is therefore well suited to script samples that were quickly executed, and where the incidental variation between the graphs is great, as indeed is often the case in the Late Mediaeval Nordic manuscripts. Supplementing the aforementioned aspects is the feature of curvature, i.e. measurement of the roundness and straightness of the strokes, also irrespective of the script sign in which it occurs.

The current investigation is largely based on the Quill Feature method as carried out by Brink et al. (2012). Some technical developments have subsequently been made, in particular the use of information on curvature, and these revisions are described in Wahlberg et al. (2014b).

2 Aim

The aim of this article is to test and evaluate the Quill Feature method as a tool for scribal attribution in an Old Swedish manuscript. The manuscript in question is Cod. Ups. C 61 (hereafter C 61), preserved at the University Library in Uppsala. It contains a number of St Birgitta's revelations in Old Swedish translation and some further texts related to St Birgitta. A number of different hands can be identified in this manuscript, most of which display great similarities while one differs significantly. The scribal question has been discussed before, in particular by G. E. Klemming (1883–84) and Jostein Gussgard (1961), and their conclusions will serve as background for the current investigation. The method and the manuscript will be described further below.

Our purpose is to evaluate the digital results from a traditional palaeographic perspective and determine the significance of the data obtained from the digital investigation. It should be emphasised that most digital investigations are carried out in technical environments, albeit with initial input from traditional philologists. For the results of these digital methods to gain acceptance with a larger group of researchers, it is necessary to apply a palaeographic perspective to the approaches, and to evaluate them by comparing the results of these investigations to those reached by traditional philologists. It is essential that the digital and the traditional paradigms meet.

As previously stated, the Quill Feature method is evaluated here as a tool for scribal attribution. It should be stressed, however, that scribal attribution is a very complex process, and often the researcher is faced with contradictory data as regards the scribal issue. The primary purpose of digital palaeographical methods is not to automatically distinguish one scribe from another. Instead, their value lies in measuring script characteristics in a completely objective way, and with the highest degree of accuracy. It is of course clear that features of the script apart from those investigated with the Quill Feature method carry weight in determining the scribe of a certain text, and for an attribution to be reliable, complementary evidence must be considered. This method should be regarded as a means to measure differences and similarities in the execution of the script, and these measurements *can be used as evidence* in the matter of scribal attribution, but they *do not automatically resolve* such issues. To obtain a fuller picture of the characteristics of a certain script sample, further measurements are also desirable, and indeed necessary to clarify individual traits.

It is furthermore clear that scribes can vary in their execution of the script, even within one period of writing. They might use a different ductus to render a ‘k’, for instance, which would result in different measurements. The interpretation of results in this type of investigation must thus be made with great care. However, one major feature of this investigation and most other applications of digital palaeography is that the methods are usually distinctly quantitative. It is through the mass of examples that the tendencies emerge, and not through the detailed analysis of a limited set of graphs. Even though a scribe may vary the ductus of ‘k’, for instance, resulting in a different type of variation in width, the large number of examples will still indicate the script tendencies.

3 Digital Palaeography and Informal Script

In many cases, digital palaeography represents digital adaptations of methods that have emerged from traditional palaeography. Traditional palaeography has worked with different criteria to characterize the distinct traits of a script, and to a large extent the material has determined the set of criteria which is suitable. Léon Gilissen (1973) used morphology, i.e. the form, as the main feature, and before the time of digital palaeography and centroids, he tried to create “average graphs” by transposing actual occurrences of letters, i.e. graphs, over each other. His method, revolutionary for its time, is actually the principle which has been implemented in certain forms of digital palaeography, such as the already mentioned SPI. Gilissen worked with manuscripts containing highly calligraphic script, and as a result the variation between graphs was small. This makes it natural that morphology has become an important tool in formulating the distinct characteristics of a script. For formulation of an average graph to be possible, or at least one that can be meaningfully contrasted with other average graphs, it is necessary that the script be very homogenous.

Objections to Gilissen’s method were raised by researchers working with material of less calligraphic execution. Hedda Gunneng (1992) noted that variation in form of the script signs in the manuscript that she was investigating was far too large to allow morphology to be the main feature for characterization of the script. She suggested other features that she maintained were better suited to script containing a large degree of variation. Of significance for the choice of criteria is really the level of execution (Formata, Libraria, Currens) rather than the style (Textualis, Hybrida, Cursiva and so forth). The carefully executed Formata script would be a suitable subject for the morphology-based analysis of Gilissen and SPI, whereas the quickly produced Currens script has to be investigated in another way.

Gunneng suggested the following criteria as relevant in the analysis of informal, quickly executed script (1992: 25–26):

1. The way in which the graphs in a word are attached to each other
2. The direction in which the strokes are drawn
3. The degree of lean in the elements that are meant to be vertical
4. The relative difference in length between minims and ascenders
5. The straightness of the lines.

The Quill Feature method measures and quantifies the features of 2, 3 and in the specific version of the method used in the current investigation, also 5 (the element of *curvature*; see further below). These features will thus comprise the criteria for the scribal attribution that is to be made here. The variation in width of the strokes stems to a large extent from the direction in which the pen has been moved, and the degree of lean is covered in the measurement of the angles.

A similar distinction to the one above regarding the focus on form vs other scriptual features can be seen in the digital methods for scribal attribution. In this field, a distinction is often made between symbol-dependent and symbol-independent approaches. The former deals with the shape of a specific script element, e.g. a letter (cf. Gilissen), whereas the latter concerns features that occur in many different script elements (cf. Gunneng). Examples of symbol-independent features are the slant and curvature of minims, ascenders and descenders, the roundness of loops and so on.

The method chosen for the present investigation focuses on symbol-independent script features. This makes it versatile as regards variation in script execution, and rather than being limited to very tidy script samples, it can therefore be used on all the mediaeval material.

When it comes to analysis of the shape of the script signs rather than their interpretion as linguistic entities, the tools used in digital analysis can be of great benefit in quantifying observations. For instance, the human eye can observe that the strokes constituting script signs vary in width, one of the key features of the present method, but it is very difficult to quantify this observation, and impossible to do so with consideration given to the exact angles at which the width varies. Human expertise is, however, necessary, firstly to determine for the computer which features should be measured, and secondly to interpret the measurements. The point of departure in this article is a combination of traditional and digital palaeography. Many useful observations have in the past been made concerning Gothic script, and it is necessary to heed these and adopt a palaeographic approach to the digital methods.

This investigation is intended to be the first step in a large-scale mapping of mediaeval Swedish scribes with digital methods. It will be followed by several further digital investigations of the script of Swedish scribes, initially those found in the charters. Characteristics of the script other than those investigated by the present method also require measurement, for instance the relative sizes of minims, ascenders and descenders, and the verticality of those script elements that are intended to be upright (cf. Gunneng above). A combination of such investigations will allow a fuller picture of the micro-palaeographic features of the mediaeval script of Sweden to emerge.

4 The Quill Feature Method

As mentioned above, the Quill Feature method measures the variation between thick and thin lines in the script, i.e. variation in width, irrespective of graph-type or grapheme. The width variation is then correlated to the direction, or the angle, in which the strokes are drawn. This estimation of direction is possible as mediaeval script, at least on parchment and paper, was produced with a quill. The quill was made of a feather which had been truncated and cut in the front. This writing tool creates certain conditions for the execution of the script, two of which are central to this method:

1. The directions in which the strokes can be drawn are limited. Scribes usually draw the strokes downwards and sideways; upward strokes are very limited; although with care they can be produced, this direction is not common.

2. Due to the pen's truncation and its incision at the top, the strokes comprising the script signs display variations in width. The relationship between thick and thin lines stems from different causes: the direction, the nature of the pen, i.e. how sharply it has been cut, and the flexibility of the pen.

The variation in width due exclusively to the nature of the pen is of course not of interest from the perspective of scribal attribution. During a period of work, a scribe can be expected to cut the pen or even exchange it, with the result that a new pattern in the distribution of thick and thin lines would arise. This variation, which derives from the writing material, is registered in the Quill Feature measures, but as the variation in width is always correlated to the script angle, it is largely (but not altogether) neutralized.

Some features of the variation between thick and thin strokes can be expected to have its origin in the individual habits of the scribe. The habitual tip angle is central in the search for individuality in the execution of the script (Brink et al. 2012; see below). This is not really a measure of width, but the angle of the pen when the greatest difference between the thick and the thin strokes is produced. It is important to remember here that the broadest strokes are not created when making a vertical stroke, as the pen then is partly tilted. It is when the pen is drawn diagonally downwards to the right (if the scribe is right handed) that the thickest strokes are created. In the same way, the narrowest strokes are not created in a horizontal stroke, but when the pen is drawn diagonally upwards to the right. And it is here that the tip angle is measured: the angle between the narrowest line and the base line (see fig. 1). It has often been assumed that this angle was kept constant by the scribes (e.g. Brink et al. 2012).

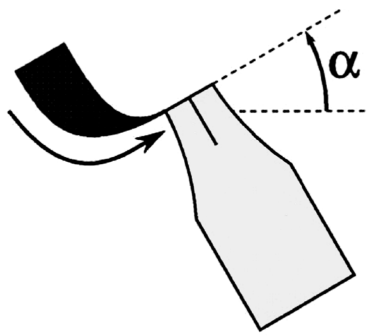

Figure 1. The Habitual Tip Angle; image from Brink et al. (2012).

It can of course be questioned how we can be certain of the fact that the habitual tip angle was a) constant for each scribe, and b) unique for each individual scribe. It is impossible to fully verify either of these statements, as the movements of the scribes lie several hundred years back in time. Still, the investigations carried out with this method (e.g. Brink et al. 2012) certainly support the assumptions. The tip angle, as estimated through the variation pattern of thin and thick strokes, seems to be constant on pages that from external evidence and general impression appear to be the work of the same scribe (adjacent pages without obvious changes in the character of the script). The details of this feature require further investigation, but the results thus far are very promising. Furthermore, one can once again point to the quantitative nature of this method. Even if scribes actually changed the tip angle, as indeed one can assume they did when the hand moved over the surface of the script, tendencies indicated by the large number of examples are likely to be correct, even where a few graphs were produced with a different angle.

Some other causes of variation in width are the following (see Brink et al. 2012):

1. Variation in force of pressure
2. Rotation of the pen.

Of these two, the variation in pressure is the most important. In a number of cases, variation in width could be explained by both these factors, but it is reasonable to assume that variation in pressure is the more common cause. The rotation of the pen would be a rather inefficient movement in the writing process, whereas variation due to force of pressure results naturally from the quill's incision at the point. However, regardless of whether difference in width is due to variation in force of pressure or rotation of the pen, the distribution of thin and thick lines can still be assumed to show an individual pattern.

When the computer measures the width of the strokes, it also, as previously mentioned, considers direction. But in each case we are given no reason for one stroke being thinner or thicker than another. By studying individual graphs, however, we can often determine with a high degree of certainty the cause of a certain instance of width variation. The images in figure 2 will serve as an illustration.

In the strokes comprising the loop at the top of the ascender, variation in width can be observed that must be attributable to different causes. At the horizontal arrows, the strokes in both graphs become thinner. The explanation for this is of course the direction, as the strokes are drawn on a slant, resulting in a thinner stroke being created. This cause of variation

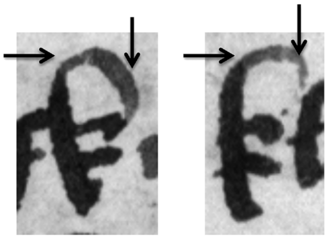

Figure 2. Two ‘k’-graphs from different hands in C 61.

in width is also significant for the mapping of a scribe’s individual habits. Although the reason for the thin strokes is the construction of the pen, the angle at which the thin strokes are created might indicate individual preference (the habitual tip angle; see fig. 1). But the vertical arrows point at variation in width that cannot be explained by the angle, but by variation in either force of pressure or ductus. These strokes are drawn in a direction in which the quill is not restricted with respect to creating width. Thus both scribes here had the possibility of creating a thick stroke, but only one did so. One explanation for this difference is, as stated, that it is caused by variation in force of pressure. According to this explanation, the scribe producing the left graph used force enough to create a stroke almost as thick as the one in the ascender, whereas the scribe producing the right graph instead reduced the force here, creating a stroke as thin as the one that is slanting up to the right (the horizontal arrow). The other explanation for this variation is that it occurred due to differences in ductus. A loop of the type in question could be created either by taking it upwards, anti-clockwise, or by adding a second stroke after the descender, in a clockwise direction (Derolez 2003: 125 ff.; 129). The former process would result in a ‘k’ of the second type in figure 2, and the latter process would give a ‘k’ of the first type. Irrespective of the cause of the variation in width, these two ‘k’s would show different patterns in an investigation with the Quill Feature method.

In figure 3, the measuring process of width vs angle is illustrated.

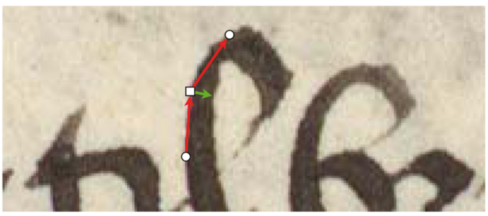

Figure 3. The measuring of width vs angle.

In this image, the box is the point from which the measure is taken. The green arrow represents the width at this point, and it also accounts for the angle at the same point, seen from a vertical perspective. As shown in this image, the width is measured at certain intervals, in the present study in the middle of a sequence of 20 pixels. The width is thus not measured at every point in the letter. All graphs on the pages under investigation are measured for width of stroke and the angle at which it is drawn. Thus each page in the manuscript can be compared to the others, and the investigation is consequently based on a complete mapping of the script signs on the pages.

A further feature that has been added in the present study to the Quill Feature method is, as noted above, curvature. This means that the computer measures the roundness vs straightness of the strokes comprising the script signs. This feature adds another dimension to the characterization of the script, one which is highly relevant when dealing with script on a Currens level. One of the prominent features of the mediaeval Cursive script is the presence of redundant loops, for instance on the top of ascenders (i.e. on 'b', 'd', 'l' etc.; see Derolez 2003: 142). These loops can be formed with different degrees of roundness, and this feature is considered with the present method.

The computer measures the outlined script features on each page, and a collective value for each page is obtained. This means that the units of measurement in the investigation relate to pages rather than individual strokes. Indeed, although every stroke of each script sign on the page is considered, the measurements are given per page. This highlights the quantitative nature of this method, as the width and curvature of each individual stroke are not given, but disappear into a collective value for a larger unit. Furthermore, the measurements are shown via a number which cannot automatically be transferred or "translated" into the actual script sign. The values from the investigation can be visualized in different ways. The value of each page can be rendered in the form of a histogram, where angle and width are the coordinates. As stated above, however, this is a statistical illustration of the measurements taken, and the value is not directly visible in the script signs. The values of the different pages can also be contrasted with each other in a scatter plot. Both these types of visualization are given in section 6 below.

All images used in this investigation were obtained under the same conditions and they all have the same resolution (600 dpi). The results of this investigation are therefore not misleading as a result of varying image quality. Variation in image quality *can* lead to different results, but at the present stage of research it is not possible to say exactly how. When comparing images from different manuscripts, great care must be taken to account for differences in light conditions, image quality and so on. In the present investigation, however, this was not a concern.

Another problem that can be encountered is that of damage to the script surface. The damage in C 61 is limited, but this is of course an important feature of this method from a general perspective. It is essential that the damaged parts of the manuscript under investigation be excluded from the measuring process, as these would distort the results. This has been done in the present investigation; damage to the script surface has been identified and eliminated.

The technical features of this method are thoroughly described in Wahlberg et al. (2014b), but a few points should be made here. The measuring process of the present investigation took approximately one day, and the computer used was a laptop of average performance. Once the programming has been completed, the computer works on its own without human supervision. However, there is no software or application specifically for this purpose, and the programming requires the special competence of an image analyst.

5 The Scribal Hands of Cod. Ups. C 61

In the current investigation, we used the manuscript C 61. The main contents of C 61 are St Birgitta's Revelations in Old Swedish translation, namely Books 3, 4, 5, 6, 7 and 8. C 61 also contains other texts, for instance a legend of St Birgitta (Vita Abbreviata), an exposition of the ten commandments and a legend of St Silvester and St Birgitta. The material of the manuscript is paper, and it is dated to the early 16th century (Andersson-Schmidt & Hedlund 1989: 31–33). It has generally been assumed that the manuscript was produced in Vadstena, as it has many of the features that are associated with manuscripts produced there (Morris 1991: 4–5). It is likely, however, that it was moved from Vadstena at an early stage and was kept in Stockholm for large parts of the 16th and the 17th centuries. In the 17th century, the manuscript reached Uppsala, and at this point the different parts that the manuscript today consists of were bound together by Johannes Loccenius (ibid. p. 5).

The issue of the scribal hands in C 61 was first discussed by G. E. Klemming (1883–84: 155–156). He identified three different scribal hands in the manuscript. Scribe 1 produced pp. 1–298, 305–354, 415–422, 425–428, 431–438, 441–444, 447–450, 453–472, 477–516, and 531–534. Klemming noted that this hand showed a great deal of variation. Scribe 2 wrote the pages to 536 that were not produced by Scribe 1. Scribe 3 wrote the rest of the manuscript, i.e. 539–1104 (pp. 537 and 538 are empty). The distribution of hands 1 and 2 is rather surprising after p. 298, as they alternate after very short intervals.

Jostein Gussgard (1961: 23) briefly touched on the issue of the scribal hands in C 61. He agreed with Klemming that pp. 539–1104 were produced by a hand that did not write anything in the first part of the manuscript. He further claimed that pp. 1–129 were written by one hand, while pp. 130–133 were written by another. Finally, he thought that pp. 137–536 were written by two separate scribes, of which possibly one could be the same as the one that produced pp. 1–129. His division into scribal hands thus differs to some extent from Klemming's, except as regards the latter part of the manuscript.

Morris (1991: 6–7, footnote 7) also comments on the scribal hands in C 61. She assumes that three hands produced the manuscript, and it appears that she concurs with Klemming's description. She also refers to Gussgard's discussion of the scribal issue, but does not explicitly state whether she regards this standpoint to be more convincing than Klemming's.

As Klemming makes the hitherto most detailed division of the pages into separate scribes, we have elected to use this as the basis of the present investigation. However, we have chosen to keep Gussgard's separation of pp. 130–133 to a hand separate from the rest. His division could not, however, be used as the basis of the investigation as a whole, as he does not make a detailed division of pp. 137–536. Thus four scribal hands are separated in the investigation. A complete overview of the parts of C 61 to be contrasted is given in table 1. Samples of the scribal hands are shown in figures 4–7.

Table 1. A division of the pages in C 61 into scribal hands.

Page Interval	Hand	Page Interval	Hand	Page Interval	Hand
1–129	1	425–428	1	453–472	1
130–133	2	429–430	3	473–476	3
134–298	1	431–438	1	477–516	1
299–304	3	439–440	3	517–530	3
305–354	1	441–444	1	531–534	1
355–414	3	445–446	3	535–536	3
415–422	1	447–450	1	537–538	–
423–424	3	451–452	3	539–1104	4

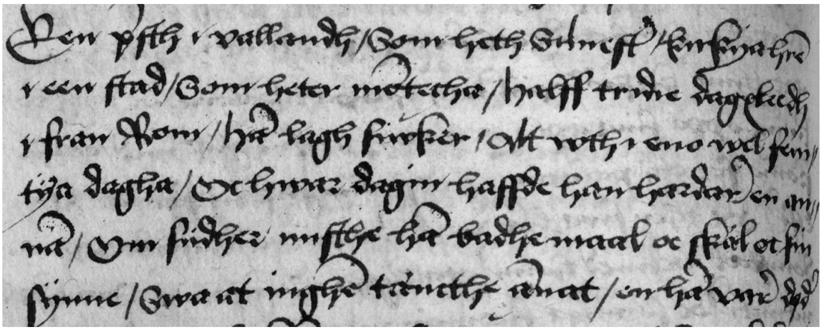

Figure 4. Hand 1.

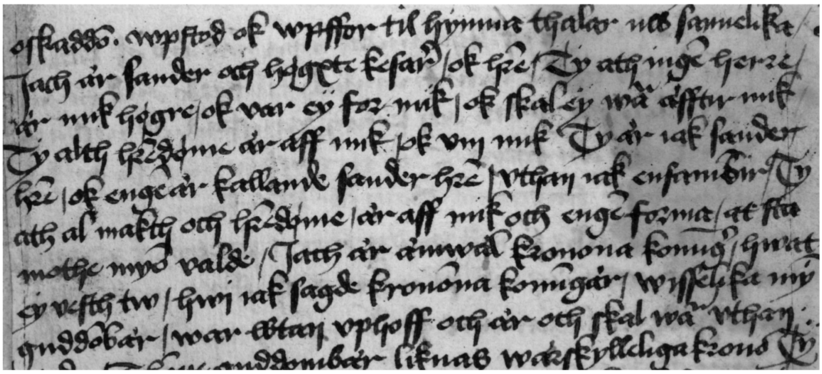

Figure 5. Hand 2.

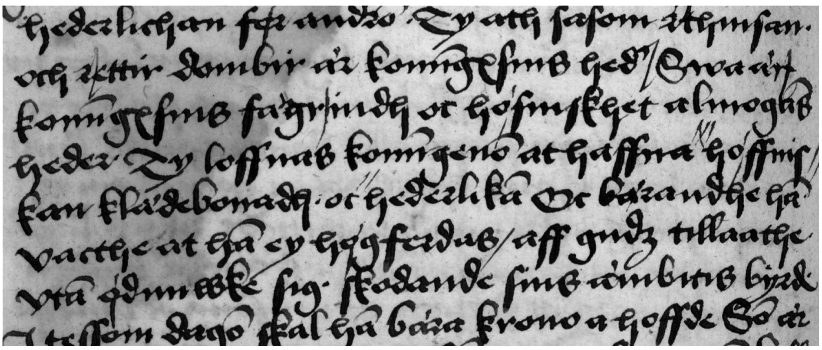

Figure 6. Hand 3.

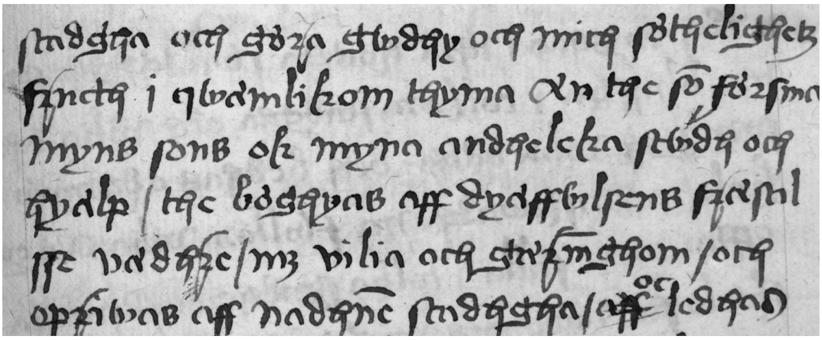

Figure 7. Hand 4.

There are a number of palaeographic differences between the four hands, for instance in the execution of 'g' and 'k'. This is illustrated in figures 8–9.

As regards the 'g', the loop under the baseline has a different form in all the examples. In 'k', there is a difference in the degree of lean in the ascender and in the form of the loop at the top of the ascender. Furthermore, the formation in the middle also shows differences. If these differences were evident only in the examples chosen in the images, i.e. representing incidental variation in the graphs, they would not be significant. However, if these differences could be seen in other graphs with the same distribution by the separate scribes, this would be an indication that different scribes had produced the different parts.

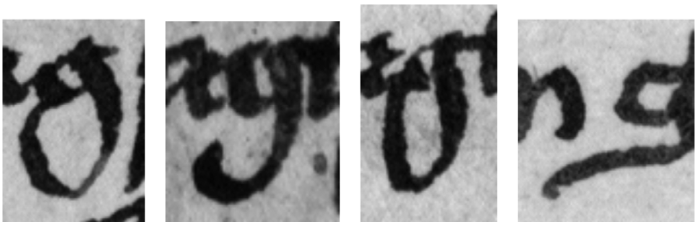

Figure 8. Examples of 'g'-graphs from hands 1, 2, 3 and 4.

Figure 9. Examples of 'k'-graphs from hands 1, 2, 3 and 4.

Klemming does not state what criteria he used when dividing the manuscript into scribal hands, but it is likely that he used palaeographic evidence, as in the cases above. It is not possible to determine, however, how systematic Klemming's classification was, but even from a more impressionistic look at the samples above, one would expect different scribes in the different cases (even though hand 2 escaped Klemming's attention).

6 Results

One of the more important aspects of the present method is the quantification of the features involved. When the computer had completed the operations described above, each page in C 61 received a set of values representing the number of edge points with a certain angle, width, and curvature. The angle, width and curvature were quantized into bins and could be depicted as a 2- or 3-dimensional histogram representing statistical variation in a page. The collection of values may also be seen as coordinates of a particular page in a high-dimensional quill feature space. It emerged that, for the pages produced by the same scribe, these values collected in clusters in this high-dimensional feature space. This means that the regularities of the measured features were relevant from an individual perspective, even though to some extent they point in different directions (see further below).

Below (figure 10) are histograms for two different pages in C 61. The pages are p. 20 (hand 1) and p. 999 (hand 4) and the graphic representation is a 2-dimensional slice of the histograms representing only angle and stroke width.

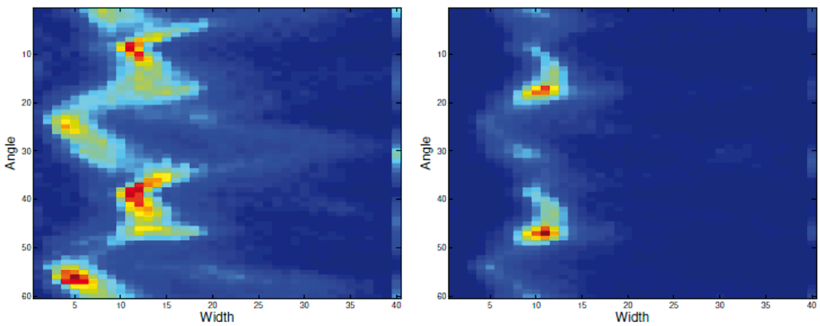

Figure 10. Histograms for pages 20 and 999 (hand 1 and 4 respectively). Red and yellow represent a high frequence of edge points with a certain angle and stroke width.

In figure 11 below, samples from the scribes of the script measured in the two histograms are given.

Earlier researchers have claimed that these two pages were written by different scribes, and this is supported by the data obtained through the Quill Feature method. Different patterns can be observed in the two histograms. As stated above, the vertical dimension in the histograms is angle, and the horizontal one is width. The non-dark blue (red and orange) parts of the histograms indicate high frequency of a combination of a certain angle and a certain width. From the histograms it is clear that the script sample which generated the histogram on the left contains greater variation in width than the one which generated the histogram on the right, as the colored (non-dark blue) sections stretch over larger areas horizontally than in the histogram on the right. It could be added that this method, if applied to script produced with a modern ballpoint pen, would render an almost completely straight vertical line in the histogram, as there would be little variation in stroke width. Such script can therefore be analyzed as regards the angles, but this information cannot be matched to the feature of width.

It should be noted that in the histograms in figure 10, the feature of curvature is not illustrated, but only angle and width. In figure 12, an image shows how the contours of the script signs are measured to obtain the curvature.

An important improvement to the Quill Feature method is the addition of measuring curvature. The varying degree of roundness vs straightness of the script signs in the Gothic script could certainly be conditioned by individuality, as noted for instance by Gunneng (1992; see above). But measuring this is very difficult, if not impossible, with manual methods. It is, however, worth mentioning one of the difficulties with the digital methods as used in this study. The histograms, although generated

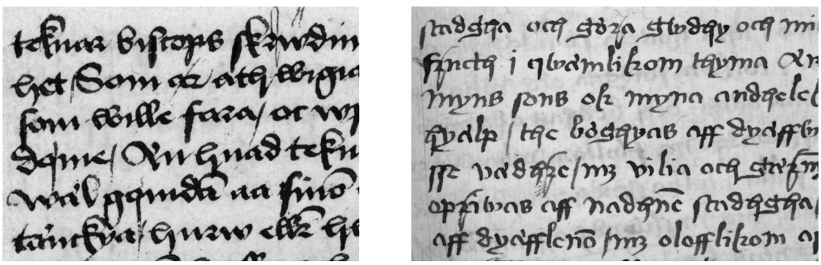

Figure 11. Samples from the scribes (1 and 4) that are illustrated in the histograms above.

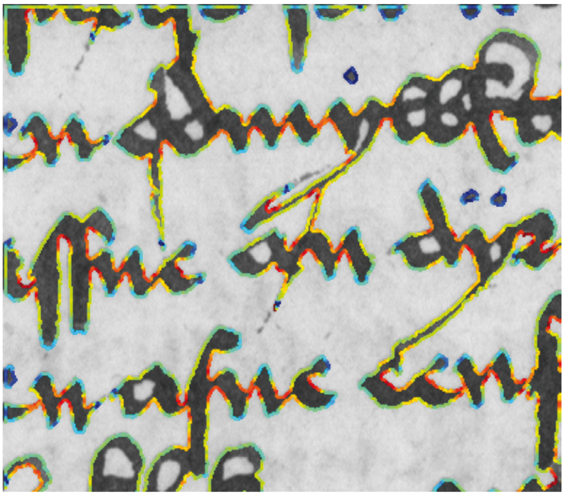

Figure 12. Measuring of the contours of the script to extract the feature of curvature.

through exact measurements of the script signs, also illustrate one of the difficulties in interpreting the data. The histograms are statistical illustrations of the data obtained through the investigation, but they do not show where in the script signs the data are observable. The measures are taken from all the occurrences of script signs on one page, but it is difficult to identify which part of the script signs the red and orange parts actually correspond to. This process also illustrates the major strength of digital palaeography, however: the computer measures phenomena that cannot be measured accurately with the human eye. Through the programming performed via this method, we are aware of which features are measured, but we cannot follow the process ourselves with the naked eye, or at least only with great difficulty.

On first impression, the pages on which the histograms are based certainly look different (see fig. 11), and further, when considering certain palaeographic features that are often accorded significance in traditional palaeographic analysis, differences are obvious (see the comparison of 'g' and 'k' in C 61 above). Traditional palaeographic analysis and the Quill Feature method coincide in their results, even though they are based on different criteria. Thus they complement each other in important ways. However, a traditional palaeographic approach and a digital method of the present type certainly map different features of the script, of which the ones generated by traditional investigation are directly visible to the human eye, whereas those identified by the digital investigation are not.

Figure 13 (also in Wahlberg et al. 2014b) below is a further illustration of the quantification of the differences between the hands. This plot is based on the full 3-D histograms from all the features measured in the method: angle, width and curvature. Because the 3-D histogram is a high-dimensional space, i.e. each histogram consists of a large number of values, we have used Principal Component Analysis (PCA) to visualize each page/histogram as a point in a three-dimensional space. PCA preserves the structure of the data and is a way of showing as much variation in this as possible in as few mathematical dimensions as possible. Thus it can be used to depict high dimensional data, but it can never show the full variance of the same data. In this 3-D plot, the different hands are marked by different colors: hand 1 is red, hand 2 is blue, hand 3 is green and hand 4 is yellow.

In this plot, every dot represents one page in C 61, and each represents one histogram such as those shown above, with the addition of the feature of curvature. Every page, and every graph on the page, is accounted

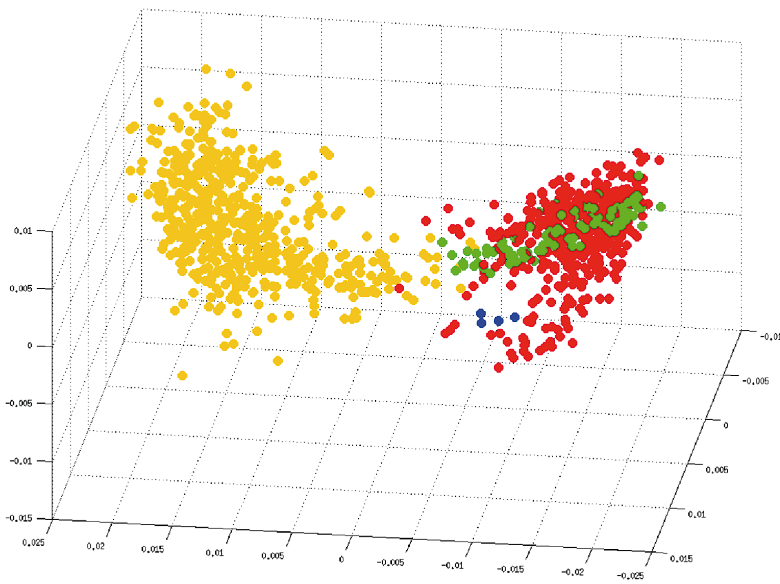

Figure 13. Hands 1–4 as measured by the algorithm used in the present study. Each dot represents one page in C 61. Hand 1 is red, hand 2 is blue, hand 3 is green and hand 4 is yellow.

for in this image, and the collected measures of the chosen method are given here. Also provided here is a statistical illustration of the measurement, and this cannot be directly converted to clear, visible characteristics of the individual graphs. Furthermore, the different axes in the plot in figure 13 do not correspond to angle, stroke width or curvature. The PCA method we employ for depicting data helps only to map similar 3-D histograms to similar points in the 3-dimensional plot.

This plot indicates that the hands, apart from hand 4, could not be automatically separated with this method, at least in this visualization. If the pages of the postulated hands were not colored, all pages except hand 4 would be inseparable in one cluster. In fact, several pages, presumably written by different scribes, actually coincide in this plot, and this would mean that they were identical in terms of the investigated features. This could indicate either that they were actually produced by the same hand (probably wrongly so), or that different hands can show identical patterns in the features measured by this method. However, due to the nature of the high-dimensional data and the limitations of PCA, feature points from different hands are likely to be more separate in our measured data than they appear in this plot, as is also indicated by results from Wahlberg et al. (2014b). This means that the measurements obtained from the investigation actually differ more than this plot indicates. Still, one should bear in mind that different script samples certainly can display great similarities.

As stated above, however, automatic scribal attribution was not the aim of this investigation, but rather measurement of the characteristics of the script. And in this respect, the Quill Feature method proved to work very well. As can be observed, the pages of the same color, i.e. those produced by the same hand, are concentrated at the same place. For instance, the pages of hand 3 (green) are not randomly spread out among the pages of hand 1 (red), but actually form a pattern. However, due to the quantitative nature of the data acquired through this method, it is difficult to say how this regular distribution should be interpreted. One of the future challenges of the version of the Quill Feature method used here is thus to optimize the depictions of the values obtained.

The crucial issue is that the method presented here, as stated above, is quantitative. Certain pages by different scribes can certainly coincide, but the mass of examples still show tendencies. Manual measurement and quantification of the features of width vs angle would be very difficult, and this obstacle is overcome by the present method. Here, exact numbers are produced, and they are obtained from all the existing graphs in the manuscript. The present investigation also shows, however, one of the weaknesses of digital approaches of the current type. The results are certainly based on exact measurements, and the similarities and differences in regards to the features angle, width and curvature of the different script samples are quantified in exact numbers. Still, the measurements (similarities and differences) are given only as numbers, and these numbers cannot easily be directly identified in the script signs.

7 Final Remarks

The investigation using the Quill Feature method was very efficient in providing exact measurements of the examined characteristics. It does not, however, work as a tool for automatic scribal attribution, as two different hands can appear very close to each other in these features, at least when PCA is used to depict the results. It is our conviction, however, that computational methods should be used to produce empirical data for human researchers to examine. The most important feature of this method, as indeed of most digital methods in palaeography, is the introduction of quantitative methods into the field. The criteria themselves, in this case variation in the width of the strokes in relation to the angle at which they are drawn, as well as curvature, have been in focus in palaeographic research for a long time, but it is not until recently, with the introduction of digital methods, that we have had the possibility of measuring these features on a large scale.

The measurements obtained from the investigation yielded important information about the regularities of the separate hands, as most pages produced by the same hand showed very similar values. But hands 1–3 all had similar values, and only hand 4 was distinctly separate from the rest. Hands 2 and 3 were also clearly separate from each other. Even though these two hands had different values and could be separated, they were both in the same cluster as hand 1 (see figure 13). This hand, very richly represented in the manuscript, produced many pages that had a value that came close to both hands 2 and 3. And as a matter of fact, the investigation provided only weak evidence regarding hand 2 and its being separate from hand 1. Thus, an investigation of the scribal issue using the Quill Feature method should be complemented by other criteria relevant to scribal attribution (palaeography, orthography and so forth). At the present stage of research, therefore, the Quill Feature method is extremely useful as a tool for describing certain characteristics of the script and as a complement in undertaking scribal attribution. The results must, however, be supplemented with other evidence.

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