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Evaluating the Historical Accuracy of Blackwork Embroidery with Fractal Analysis

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Abstract

The intricate monochromatic embroidery that graced the collars and cuffs of Renaissance nobility and domestic materials from that era has been little studied beyond the historical costuming and crafting communities. This style, known as blackwork, for it was traditionally done in black silk on white linen, exemplifies how complex and visually-appealing designs can arise from repetition of simple forms, often demonstrating the fractal property of self-similarity. Though most blackwork patterns are not true fractals, fractal analysis offers a means of objectively quantifying their complexity and new lens through which to examine this embroidery technique. The purpose of this study was to look for trends that could be used to evaluate the historical accuracy of blackwork patterns. Images of historical patterns from the Renaissance period, historically-inspired, and modern patterns were gathered from eight published books on blackwork. The fractal dimensions of these patterns were calculated using FracLac, a fractal analysis plugin for the ImageJ software. Subsequent statistical analyses revealed several significant differences between the fractal dimensions of patterns for fillings, borders, and complete projects. Though there was some variation, a trend noted was that Renaissance-era patterns had a fractal dimension around 1.75.

Introduction

In the field of visual arts, the Renaissance was the era of the grand masters. Leonardo da Vinci, Donatello, Michelangelo, Titian, Botticelli, Raphael, and many more well-known painters and sculptors produced works renowned for their skillful representationalism, intriguing symbolism, and evocative use of light and color. However, as the *Mona Lisa* was being painted, as *David* was being carved, another form of art was being quietly stitched by artists unknown.

Embroidery, particularly on garments, reveals the patterns, motifs, and visual elements people chose to incorporate into their everyday lives and, thus, insight into what those everyday lives were like. Perhaps because it was abstract and monochromatic, possessing qualities more akin to the Art Deco style or Neoplasticism of the early twentieth century; perhaps because it was women's work, relegated to the domestic sphere and seen as a mere commodity; or, most likely, a combination of these factors, the blackwork embroidery of the Renaissance has hitherto been the subject of minimal formal scholarship, despite remaining of great interest to hobbyists and historical crafters.

In addition to being abstract and monochromatic, blackwork embroidery is often characterized by a high level of detail. Though this classification seems vague, it is not merely a subjective assessment. The level of detail can be quantitatively measured via fractal analysis, a set of mathematical methods for calculating the fractal dimension and other fractal characteristics of data, which can be used as scores of complexity. In fact, the abstract and monochromatic qualities of blackwork embroidery make it ideal for fractal analysis, which best describes nonrepresentational shapes and processes images in a binary black and white form.

This exploratory study uses fractal analysis to examine historical and modern patterns of blackwork embroidery, looking for trends that can be used to measure historical accuracy.

Blackwork embroidery, so named for the black silk threads traditionally used to stich the designs onto white or off-white linen, was most popular in sixteenth- and seventeenth-century England. A popular legend claims it was introduced to the country by Catherine of Aragon, first wife of Henry VIII, though historical evidence suggests that Queen Catherine only popularized an existing technique which had originated in northern Africa, appeared in Spain under Moorish influence, and gradually made its way from Spain to England.[1] Black-on-white embroidery clearly existed in England prior to Catherine's arrival in 1501, as evidenced by, among other things, its mention in Chaucer's "The Miller's Tale," which dates from the period 1390-1400: "White was her smock, and embroidered all in front / And also behind, around her collar, / With coal-black silk, within and also without."[2] Nevertheless, blackwork enjoyed its greatest heyday in Renaissance England, where it adorned countless garments and household articles belonging primarily to the upper classes. The technique was commonly used as a substitute for lace, as it was cheaper to produce, and it often appeared as an edge decoration for collars and cuffs of smocks and chemises.[3] While not as prevalent as in England, blackwork was also popular in continental European countries like Spain, Italy, and Germany during the Renaissance era.

The term "blackwork" encompasses a range of techniques. The earliest recorded blackwork is highly geometric in nature and was produced using counted-thread techniques and designed to be reversible. This form of blackwork is most associated with Spanish influence and

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1. Toolika Gupta, "Kasuti and Blackwork: Twin Sisters or Just Duplicates?," *Textiles and Clothing Research Centre e-Journal* 3, no. 6 (August 2019): 18, https://www.tcrc.in/wp-content/uploads/2020/07/V3i6-Article_4_TG.pdf.

2. Geoffrey Chaucer, "The Miller's Prologue and Tale," Harvard's Geoffrey Chaucer Website - Text and Translations: 3238-3240 https://chaucer.fas.harvard.edu/pages/millers-prologue-and-tale.

3. Mary Gostelow, Blackwork (North Chelmsford: Courier Corporation, 1998), 13.

with Queen Catherine of Aragon; thus, it was often called "Spanysshe work."[4] The reversibility of early blackwork was achieved with the double running stitch, also known as the Holbein stitch, after Hans Holbein the Younger, court painter to Henry VIII.[5] Holbein's painstaking depictions of blackwork embroidery in his portraits of the English nobility preserved many designs now lost to time due to the corrosive nature of the oak gall- and iron-based dye used to blacken the thread. Figure 1 depicts a famous portrait of Jane Seymour along with a pattern of the blackwork embroidery that appears on her sleeve, a prime example of "Spanysshe work."

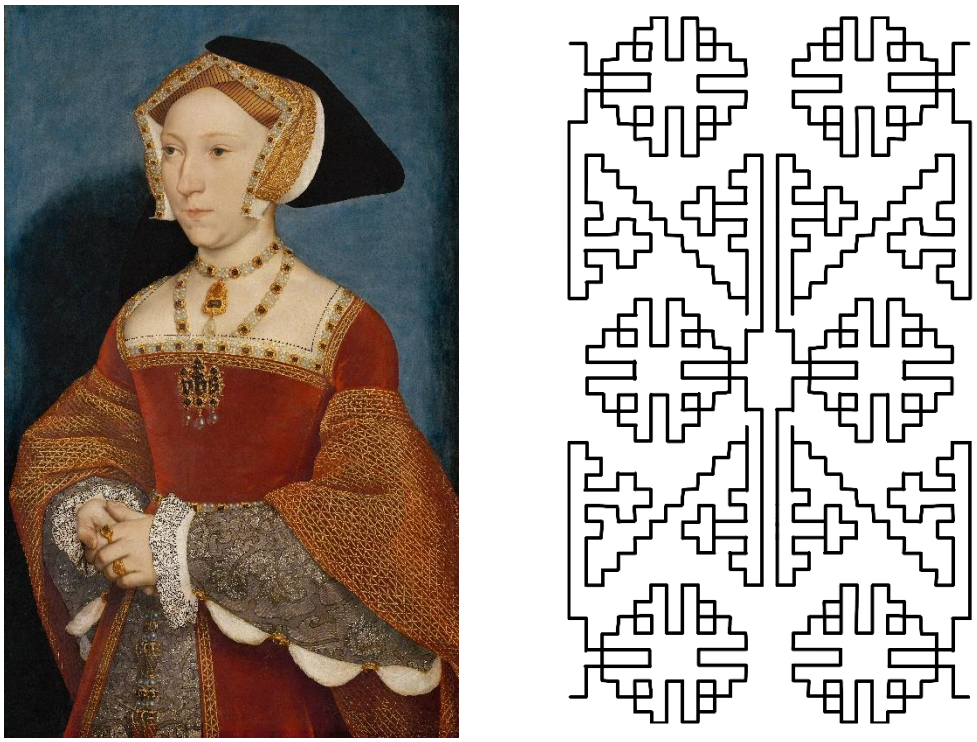

Figure 1. Portrait of Jane Seymour by Hans Holbein the Younger and pattern for blackwork sleeve cuff from *The Art of Blackwork Embroidery* by Rosemary Drysdale.

4. Rissa P. Root, "A Blackwork Embroidery Primer," last modified 2009, https://prettyimpressivestuff.com/blackwork.htm.

5. Gostelow, *Blackwork*, 46.

Later blackwork incorporated more freehand scrolling and floral designs, which may have been filled with counted-thread geometric patterns. This shift to a more recognizable subject matter reflects larger social trends; the Victoria and Albert Museum notes that "[t]he predominance of floral motifs … reflects the growing fascination with flowers in England during the 16th century and the development of domestic gardens,"[6] and Rissa Root cites the black and white plates created with the printing press as a source of inspiration for many embroiderers.[7] The prosperity of the Elizabethan era made silk more widely available than it had previously been, allowing for larger designs that fully covered garments rather than just adorning the edges. Portraiture of Elizabeth I reveals that the queen herself was particularly fond of blackwork and wore it often, as can be seen in Figure 2.

Figure 2. Portrait of Queen Elizabeth I wearing a dress with scrolling and floral designs characteristic of later Renaissance blackwork.

6. *Smock Part*, silk embroidery on linen, 1575-1585, Victoria and Albert Museum, London, UK. http://collections.vam.ac.uk/item/O78732/smock-part-unknown/.

7. Root, "A Blackwork Embroidery Primer."

Although blackwork fell out of fashion in England in the later seventeenth century, it experienced a revival in the nineteenth and twentieth centuries. Once again, the style shifted. Embroiders used geometric fill patterns of varying density to create shading effects and depict scenes "that look more drawn than stitched."[8] Sidney Eileen notes that shading is an advent of modern blackwork; Elizabethan embroiders used only "very limited shading techniques" created with the "running stitch, stab stitches, or buttonhole stitch."[9] Modern blackwork embroiderers also tend to use evenweave fabric to facilitate stitch counting and produce designs in cotton thread on cotton, as this is less expensive than silk on linen. While Renaissance blackwork was sometimes sewn using colored or metallic threads, with scarletwork, goldwork, and silverwork being particularly popular, modern embroiders create designs with threads of every color of the rainbow, as seen in Figure 3.

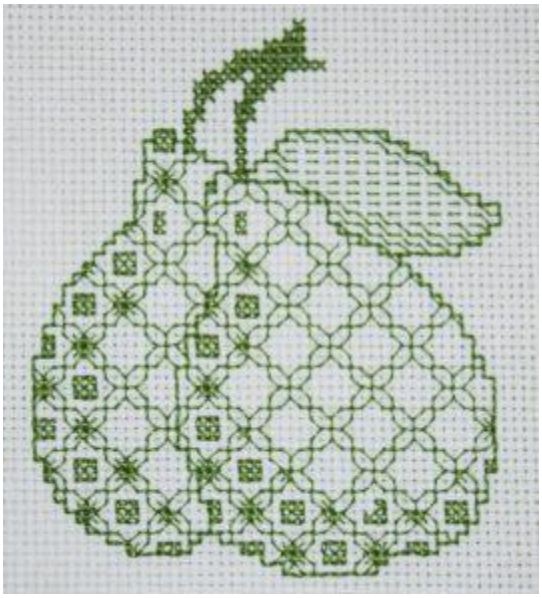

Figure 3. A sample of modern blackwork using both a shading technique and colored thread.

8. Root, "A Blackwork Embroidery Primer."

9. Sidney Eileen, "Basics of Elizabethan Freehand Blackwork Embroidery," last modified July 24, 2019, https://sidneyeileen.com/artisan-works/embroidery-articles-and-tutorials/basics-of-elizabethan-freehand-blackwork-embroidery/.

Despite the vast creative potential of modern blackwork, interest in Renaissance-era blackwork persists among historical costuming enthusiasts, such as attendees of Renaissance Faires or members of the Society for Creative Anachronism. It is from this community that a large portion of scholarship on blackwork embroidery has come, as there is a general interest in producing designs as historically accurate as possible. Not wanting to be limited to only the few blackwork designs that have been preserved on period garments or depicted in period paintings, many embroiders create their own or turn to published blackwork designs that are "historically-inspired." The goal of the current research is to provide an objective means of evaluating the historical accuracy of these designs based on fractal analysis.

Recently, blackwork embroidery has caught the interest of another scholarly community, that of mathematics and computer science. In "The Graph Theory of Blackwork Embroidery," Joshua Holden classifies the path the needle and thread must travel when stitching a reversible blackwork pattern as a digraph with vertices at the points where the thread passes from one side of the fabric to the other. He uses this to prove that every connected blackwork pattern can be stitched reversibly with one thread. Then, Holden classifies a reversible blackwork pattern as a 2-uniform multigraph and determines that, in order to be stitched unidirectionally, it must possess an Aragonian circuit, named for Queen Catherine of Aragon, which is a "Eulerian circuit where the two edges {x, y} are both traversed in the order x, {x, y}, y and are traversed with opposite parities."[10] Holden concludes by discussing how his theorems could be generalized to apply to situations in abstract graph theory that would be impossible to physically represent, like instances of more than two sides of fabric.

10. Joshua Holden, "The Graph Theory of Blackwork Embroidery," in *Making Mathematics with Needlework: Ten Papers and Ten Projects*, ed. Sarah-marie Belcastro and Carolyn Yackel (Boca Raton: CRC Press, 2007), 10.

Taking another mathematical approach to blackwork embroidery, April Grow has developed a shape grammar with set of rules for shape transformations and a user interface to facilitate the tedious process of blackwork pattern generation. Her interface divides pattern elements into edges and nodes and presents users with a series of choices regarding how to expand and combine these elements, then exports the final pattern to an embroidery machine that stitches it. One challenge Grow encountered in developing her interface was that not all patterns generated were aesthetically pleasing to human observers. She overcame this by noting visual characteristics such as symmetry, repetition, and self-similarity in traditional blackwork embroidery and including the capability for the designer to manipulate these features in the interface. These options allow Grow's shape grammar to automatically generate patterns which are more satisfying and more like existing blackwork patterns designed by humans.[11]

The property of self-similarity which Grow observed in blackwork embroidery is one of the defining characteristics of fractals. By definition, a self-similar pattern is composed of smaller replicas of the same pattern. In true fractals, the replicas are themselves composed of smaller replicas, which are in turn composed of even smaller replicas, ad infinitum. However, a pattern need not be truly fractal to be analyzed through the lens of fractal mathematics. Many complex naturally occurring patterns, such as biometric readings,[12] forest growth,[13] human

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11. April Grow, "Blackwork Embroidery Pattern Generation Using a Parametric Shape Grammar," *Proceedings of the 8th International Conference on Computational Creativity*, 2017, http://www.creweltech.com/wp-content/uploads/2016/03/Siggraph2016Blackwork.pdf.

12. Gabriella Captur et al., "Community Delivery of Semiautomated Fractal Analysis Tool in Cardiac MR for Trabecular Phenotyping," *Journal of Magnetic Resonance Imaging* 46, no. 4 (2017): doi:10.1002/jmri.25644.

13. Radu-Daniel Pintilii et al., "Using Fractal Analysis in Modeling the Dynamics of Forest Areas and Economic Impact Assessment: Maramureș County, Romania, as a Case Study," *Forests* 8, no. 1 (2017): doi:10.3390/f8010025.

movement,[14] biomedical images,[15] and geological[16] and astrophysical[17] phenomena, are better described with fractal geometry than traditional Euclidean geometry.

The metric used in most applied fractal studies is fractal dimension, a measure of change in detail with change in scale. The fractal dimension of a fractal or fractal-like image is a number between one and two, representing that the area of interest is neither a one-dimensional line not a fully two-dimensional plane. A fractal dimension closer to two indicates a pattern of higher complexity, as it is closer to filling a two-dimensional space. Conversely, a fractal dimension closer to one indicates a lower complexity. The standard method of calculating fractal dimension is known as the box-counting method. This entails covering an image with increasingly smaller grids of square boxes and recording the edge length of the boxes (ε) and the number of boxes which cover the area of interest (N) at each iteration. The fractal dimension (D_F) is

$$D_F = \lim_{\varepsilon \to 0} \frac{\log N}{\log \varepsilon}.$$[18]

There exist numerous software packages capable of calculating the fractal dimension of digital images. This study used Fraclac, a plugin for the ImageJ software. ImageJ is a java-based

14. Vivien Marmelat and Ryan L. Meidinger, "Fractal Analysis of Gait in People with Parkinson's Disease: Three Minutes is Not Enough," *Gait & Posture* 70 (2019): doi:10.1016/j.gaitpost.2019.02.023.

15. Nicolly Oliveira-Santos et al., "Influence of Phosphor Plate–Based Radiographic Image Specifications on Fractal Analysis of Alveolar Bone," *Oral Surgery, Oral Medicine, Oral Pathology and Oral Radiology* 128, no. 4 (2019): doi:10.1016/j.oooo.2019.06.011.

16. Xinxin He et al., "Effects of Coal Pore Structure on Methane-Coal Sorption Hysteresis: An Experimental Investigation Based on Fractal Analysis and Hysteresis Evaluation," *Fuel* 269 (2020): doi:10.1016/j.fuel.2020.117438.

17. S. De Franciscis et al., "Fractal Analysis Applied to Light Curves of δ Scuti Stars," *Monthly Notices of the Royal Astronomical Society*, May 2018, doi:10.1093/mnras/sty2496.

18. Audrey Karperien, "Background: Fractals and Fractal Analysis," Fraclac for ImageJ, last modified 2012, https://imagej.nih.gov/ij/plugins/fraclac/FLHelp/TheoryStartUpScreen.htm.

image processing program developed by Wayne Rasband at the National Institutes of Health.[19] Fraclac, short for Fractal Dimension and Lacunarity is a plugin developed by Audrey Karperien capable of calculating the fractal dimension of binary images with several variations of the box-counting method. Both FracLac and ImageJ are free and open source and have been used in studies similar to the current research.[20] Additionally, Hadzieva et al. report that Fraclac is one of the most versatile, accurate, and user-friendly fractal analysis programs of the ten they reviewed.[21]

The precedent for using fractal analysis to study human-produced artwork was set in a 1999 article by Taylor, Micolich, and Jonas, first published in *Nature*. The authors use the box-counting method to calculate the fractal dimension of various drip paintings by the abstract expressionist painter Jackson Pollock. The article is brief, barely more than a report of findings and conclusions they expound upon in subsequent publications; however, it was the first publication to connect fractal analysis and art in a meaningful way. Rather than merely using fractal dimension to describe the complexity of Pollock's images, the authors suggest that it could become a means of objectively validating works as Pollock's and dating them in his career.[22] In another article published that same year, Taylor, Micolich, and Jonas report more details of their research. They identify a distinction in the paintings' fractal dimensions at larger

19. "ImageJ," RSB, last modified March 2021, https://imagej.nih.gov/ij/.

20. Jessica Robkin, "Fractal Analysis Applied to Ancient Egyptian Monumental Art," (master's thesis, Florida Atlantic University, 2012), ProQuest (1522094).

21. Elena Hadzieva et al., "Review of the Software Packages for Estimation of the Fractal Dimenaion," in *ICT Innovations 2015 Web Proceedings*, ed. S. Loshkovska and S. Koceski (2015), xx, https://proceedings.ictinnovations.org/attachment/paper/376/review-of-the-software-packages-for-estimation-of-the-fractal-dimension.pdf.

22. Richard P. Taylor, Adam P. Micolich, and David Jonas, "Fractal Analysis of Pollock's Drip Paintings," *Nature* 399, no. 422 (June 1999): doi:10.1038/20833.

and smaller scales because of the different types of fractal patterns created by Pollock's movements and the splattering process of the paint, as well as a general increase in fractal dimension over the course of Pollock's career. Additionally, they analyze the fractal dimension of different layers of paint and conclude that Pollock largely established the fractal dimension of the overall piece in the first layer of paint he applied to the canvas then merely made small refinements as he added subsequent layers of various colors.[23]

Taylor, Micolich, and Jonas justify their exploration of the fractal properties of Pollock's work by explaining that nature was likely an inspiration for Pollock's art and that his unconventional method of splattering paint on a canvas could have led to movements that, like many natural phenomena, can best be described by fractal geometry. They further speculate that, even though Pollock's paintings were created before the discovery of fractal mathematics, the enduring appeal of his work may be due to his unknowing use of fractals, "the language of nature."[24]

Their work was not without its detractors. In a 2006 article, Jones-Smith and Mathur dispute Taylor, Micolich, and Jonas's claim that fractal analysis could potentially authenticate paintings and use of the word "fractal" to describe Pollock's paintings because of the limited scale at which they exhibit fractal properties. Jones-Smith and Mathur then use fractal analysis to show that an image they drew of a haphazard collection of stars in Adobe Photoshop is fractal in nature.[25] In a reply to Jones-Smith and Mathur, Taylor, Micolich, and Jonas defend their

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23. Richard P. Taylor, Adam P. Micolich, and David Jonas, "Fractal Expressionism," *Physics World* 12, no. 10 (October 1999): doi:10.1088/2058-7058/12/10/21.

24. Taylor, Micolich, and Jonas, "Fractal Expressionism."

25. Katherine Jones-Smith and Harsh Mathur, "Revisiting Pollock's drip paintings," *Nature* 444, no. 7119 (November 2006): doi:10.1038/nature05398.

characterization of Pollock's work as fractal, as numerous other studies of fractal patterns in nature work with fractals of limited scales. Moreover, they provide mathematical evidence that the haphazard star drawings are not necessarily fractal and that Jones-Smith and Mathur's box-counting analyses were flawed.[26] The current researcher sides with Taylor, Micolich, and Jonas in this scholarly discourse and, thus, considers it appropriate to refer to blackwork patterns as fractal despite the limited scale at which they demonstrate self-similarity.

Later studies by Taylor and other researchers further delve into the fractal properties of Jackson Pollock's artwork and test Taylor, Micolich, and Jonas's theories about using fractal analysis for authentication and to explain visual appeal.

In a 2002 article, Taylor, Micolich, and Jonas attempt to answer how it was possible for a human to create fractal patterns before the discovery of fractals. The authors first discuss how fractal patterns, a product of chaotic processes, have been observed throughout nature in phenomena such as trees, clouds, lightning, and flames and mention that Pollock's work is frequently described as organic, reminiscent of such phenomena, from which he likely drew inspiration. To determine how Pollock constructed his fractal drip paintings, the authors analyze video footage from 1950 of Pollock creating one of his paintings and digitally deconstruct other paintings into their constituent layers. They conclude that the final fractal dimension of the paining was largely determined by the initial "anchor layer" of paint Pollock applied to the canvas, and other layers in other colors of paint only slightly refined the fractal dimension of the entire work. Although Taylor, Micolich, and Jonas discuss this construction process in their previous publications, their new analysis of the video allowed them to study Pollock's construction of one of these "anchor layers" over time. They note that Pollock's process entailed

26. R. P. Taylor, A. P. Micolich, and D. Jonas, "Revisiting Pollock's drip paintings (Reply)," *Nature* 444, no. 7119 (November 2006): doi:10.1038/nature05399.

creating small, disconnected clusters of paint before connecting them across the larger work, making the painting more self-similar as he did so.[27]

In a 2007 study building on Taylor, Micolich, and Jonas's research identifying trends in the fractal dimension of Pollock's paintings over time and over the course of a painting's construction, Taylor et al. formulate a set of objective criteria which they believe to be unique to Pollock's work. Then, they analyze the fractal properties of 37 drip paintings created by undergraduate student volunteers and 14 paintings supplied by private collectors. None of these paintings meet the criteria of Pollock's work, which lends credibility to their proposal that fractal analysis could be used as a means of authentication.[28]

Another area of interest for fractal analysis of art has been perceptual studies. Taylor, Micolich, and Jonas, in their examination of how Jackson Pollock constructed his paintings, also discuss how people may perceive them. They note that art historians divide Pollock's work based on his artistic development into his "preliminary," transitional," and "classic" phases, and most highly esteem paintings in the classic phase, which were made later in Pollock's life. These paintings also have higher fractal dimensions than Pollock's earlier works, which suggests that people prefer artwork with higher fractal dimensions.[29] Spehar et al. report that, in a survey which included computer-generated, human-produced, and naturally occurring fractal images, participants exhibited a high preference for images with a fractal dimension between 1.3 and 1.5

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27. Richard P. Taylor, Adam P. Micolich, and David Jonas, "The Construction of Jackson Pollock's Fractal Drip Paintings," *Leonardo* 35, no. 2 (April 2002): doi:10.1162/00240940252940603.

28. R.P. Taylor et al., "Authenticating Pollock Paintings Using Fractal Geometry," *Pattern Recognition Letters* 28, no. 6 (2007): doi:10.1016/j.patrec.2006.08.012.

29. Taylor, Micolich, and Jonas, "The Construction of Jackson Pollock's Fractal Drip Paintings," 206.

and a low preference for images outside that range.[30] Taylor et al. find that a variety of biometric readings, including skin conductance and quantitative electroencephalogram response, are most positive when study participants view fractal images in the 1.3 to 1.5 range. Additionally, when tracking the eye movement of volunteers observing Jackson Pollock's fractals, Taylor et al. find the fractal dimension of the saccade to fall around 1.5, regardless of the fractal dimension of the work being observed. They speculate that the aesthetic appeal of fractals of various forms may be due to the proximity of this biometric measurement to the preferred fractal dimension range of 1.3 to 1.5.[31]

While research has identified the fractal dimension preference range of 1.3 to 1.5 as a general trend, it is not universal. In a 2016 article, Street et al. report findings from a survey with a larger sample size and greater cultural diversity than previous research. Their general findings are consistent with the 1.3 to 1.5 trend; however, they also analyze the results with respect to other factors, such as location and gender, and find enough variability to suggest that various factors influence an individual's preferred range of fractal dimension, which may not necessarily be 1.3 to 1.5.[32] Bies et al. find that the 1.3 to 1.5 preference range does not apply to exact fractals and demonstrate that fractal dimension is not the only quality of an image that drives visual preference. Their survey asked participants to rate several exact fractal images based on their aesthetic appeal. Participants generally gave the highest rating to the image with the highest

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30. Branka Spehar et al., "Universal Aesthetic of Fractals," *Computers & Graphics* 27, no. 5 (2003): doi:10.1016/s0097-8493(03)00154-7.

31. Richard P. Taylor et al., "Perceptual and Physiological Responses to Jackson Pollock's Fractals," *Frontiers in Human Neuroscience* 5, no. 60 (June 2011): doi:10.3389/fnhum.2011.00060.

32. Nichola Street et al., "A Complex Story: Universal Preference vs. Individual Differences Shaping Aesthetic Response to Fractals Patterns," *Frontiers in Human Neuroscience* 10, no. 213 (May 2016): doi:10.3389/fnhum.2016.00213.

fractal dimension and the lowest rating to the image with the lowest fractal dimension. Participants also tended to prefer symmetrical images over nonsymmetrical ones; however, a higher degree of recursion or fractal dimensionality mitigated this trend.[33]

Fractal dimension of visual images has many other perceptual and psychological connections. For example, it also appears to be linked to pareidolia, the tendency to perceive familiar images where none exist, such as seeing faces in clouds. In a study of the fractal dimensions of Rorschach Inkblots, Taylor et al. find that people tend to perceive more shapes in inkblots with a lower fractal dimension.[34] Forsythe, Williams, and Reilly try to link fractal dimension of artwork to the mental state of the artist rather than only that of the viewer. They measure the fractal dimensions of paintings by seven artists and find that artists who suffered from Alzheimer's and Parkinson's tended to produce works with lower fractal dimension as they aged. However, the results of Forsythe, Williams, and Reilly's study are somewhat confounded by the enormous variation between the artists' individual styles.[35]

Jessica Robkins observed the fractal property of self-similarity in ancient Egyptian monumental art, particularly in the repetition of figurative aspects, and hypothesized that fractal dimension may be a way of tracking chronological and regional variations in the art. Although the data she gathered do not support this hypothesis, suggesting instead that the fractal dimension

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33. Alexander J. Bies et al., "Aesthetic Responses to Exact Fractals Driven by Physical Complexity," *Frontiers in Human Neuroscience* 10, no. 210 (May 2016): xx, doi:10.3389/fnhum.2016.00210.

34. R. P. Taylor et al., "Seeing Shapes in Seemingly Random Spatial Patterns: Fractal Analysis of Rorschach Inkblots," *PLOS ONE* 12, no. 2 (February 2017): doi:10.1371/journal.pone.0171289.

35. Alex Forsythe, Tamsin Williams, and Ronan G. Reilly, "What Paint Can Tell Us: A Fractal Analysis of Neurological Changes in Seven Artists," *Neuropsychology* 31, no. 1 (2017): doi:10.1037/neu0000303.

of Egyptian art remained remarkably consistent across several centuries due to the strict conventions of the ancient Egyptian style, it remains to be seen whether this is true of other forms of art where chronological and regional stylistic changes are more pronounced.

Fractal analysis provides insight into complex phenomena in a wide variety of fields. And, in the field of art, fractal dimension provides an objective metric with which to describe nonrepresentational or highly-abstracted images. It is no accident that so much research has focused on the fractal qualities of the ineffable drip paintings of Jackson Pollock.

Like Jackson's Pollock's work, blackwork patterns, especially those in the Elizabethan period, appear to derive inspiration from nature. Although the scarcity of available blackwork samples from the Renaissance makes impossible any analysis of individual artists' changing styles, fractal dimension may reflect the observable chronological trends in the styles of blackwork patterns, from geometric Spanysshe work, to scrolling floral patterns, to modern designs that incorporate complicated methods of shading.

However, the primary goal of this study is to assess the viability of fractal analysis as a test of the historical accuracy of historically-inspired blackwork patterns. If clear trends, such as those Taylor et al. observe in the construction and chronological development of Jackson Pollock's artwork and later use to authenticate his paintings, emerge in the historical blackwork patterns studied, historically-inspired blackwork patterns can be analyzed to see if they demonstrate these same trends. Presumably, this will mean that these historically-inspired patterns have the same "look" as authentic patterns without merely being exact replicas, which is a goal of historically-inspired costume. Thus, this research has the potential to both provide new insight about a little-studied form of Renaissance art and help modern embroiders and historical costume designers continue this tradition.

Materials and Methods

The blackwork patterns analyzed in this study were gathered from eight printed books on blackwork embroidery, each of which will be discussed in further detail below. Although numerous blackwork patterns can be found on the internet, the large variation in image quality would have introduced an unwanted confounding variable. Moreover, online patterns were less likely to have consistent and accurate attributions to the designer, date, and source than those appearing in published works.

To ensure consistency of image resolution, the printed patterns were scanned using a Brother MFC-J805DW scanner on the highest setting, 1200 x 1200 dpi. The pages were then transferred to Adobe Photoshop, where the blackwork patterns were cropped and edited in preparation for fractal analysis.

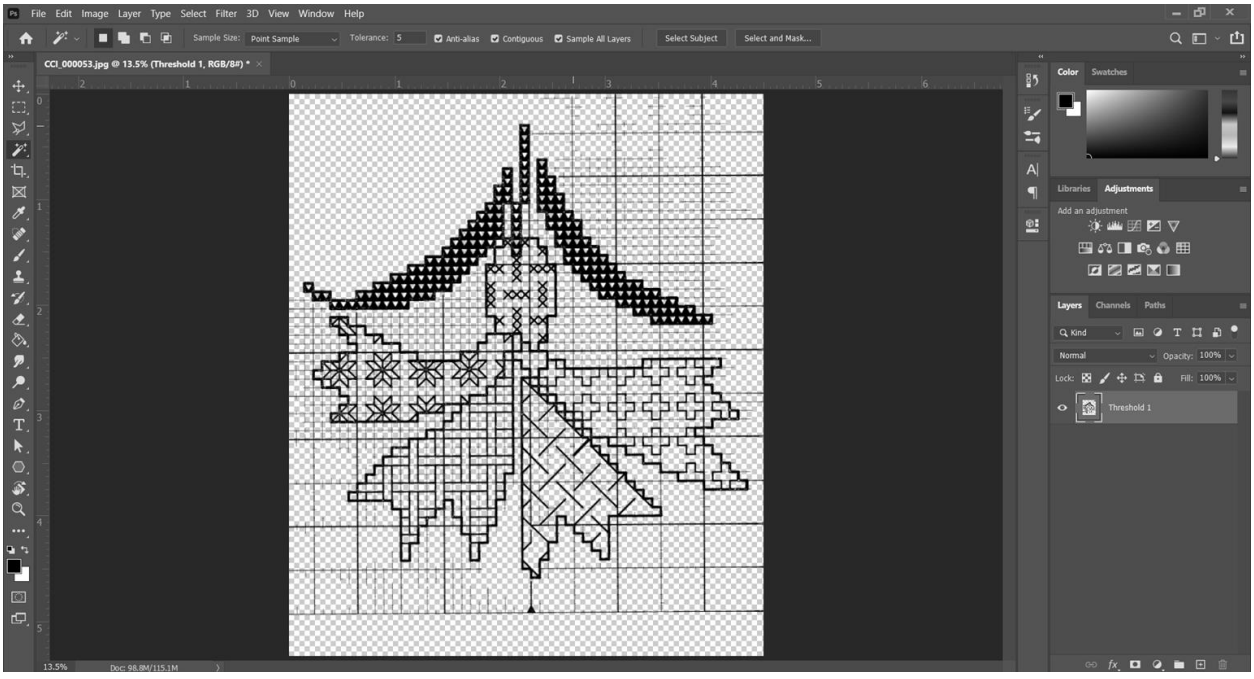

Figure 4. The Eraser tool was used to remove grid backgrounds from blackwork patterns. Pattern by Jill Carter Nixon from *The New Anchor Book of Blackwork Embroidery Stitches*.

The goal of the editing was to make the pattern the sole subject of the image. Text, backgrounds, and grid lines were removed from the patterns using the Brush, Eraser, and Selection tools (Figure 4). When removing the background proved too complicated, as was often the case with patterns that were photographed already embroidered on cloth, the pattern was traced in a new layer using the Pen or Brush tool. After the removal of extraneous details, the patterns were converted to binary images via the Threshold function, as illustrated in Figure 5. Occasionally, patterns found in the books comprised several different colored lines, either to clarify directions like stitch order or to encourage the use of different colored threads. When this occurred, the pattern was treated as if it would be stitched entirely in black thread, so the colors were darkened to black using Selective Color adjustments prior to thresholding.

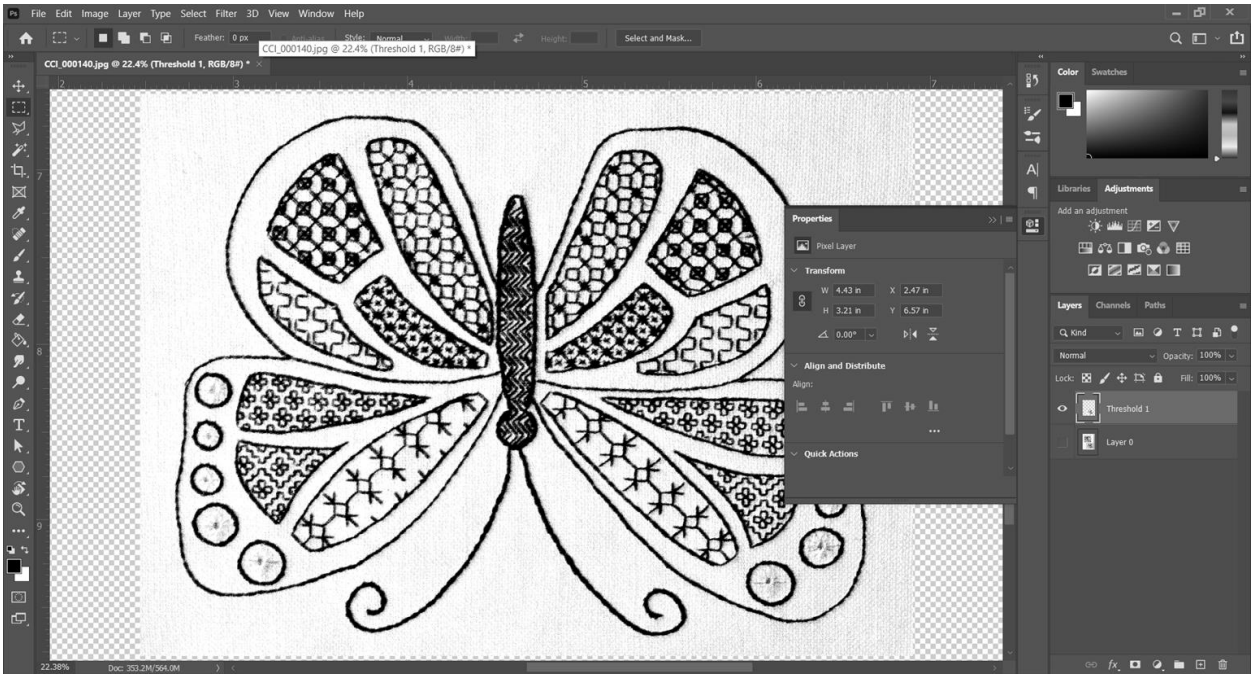

Figure 5. A stitched blackwork pattern after thresholding. Pattern by Rosemary Drysdale from *The Art of Blackwork Embroidery*.

A total of 287 pages containing 869 individual blackwork patterns were processed. The edited patterns were exported as PNG files and loaded into ImageJ in batches. The FracLac plugin was used to calculate the fractal dimension of each image file using the default settings and with a locked white background (Figure 6).

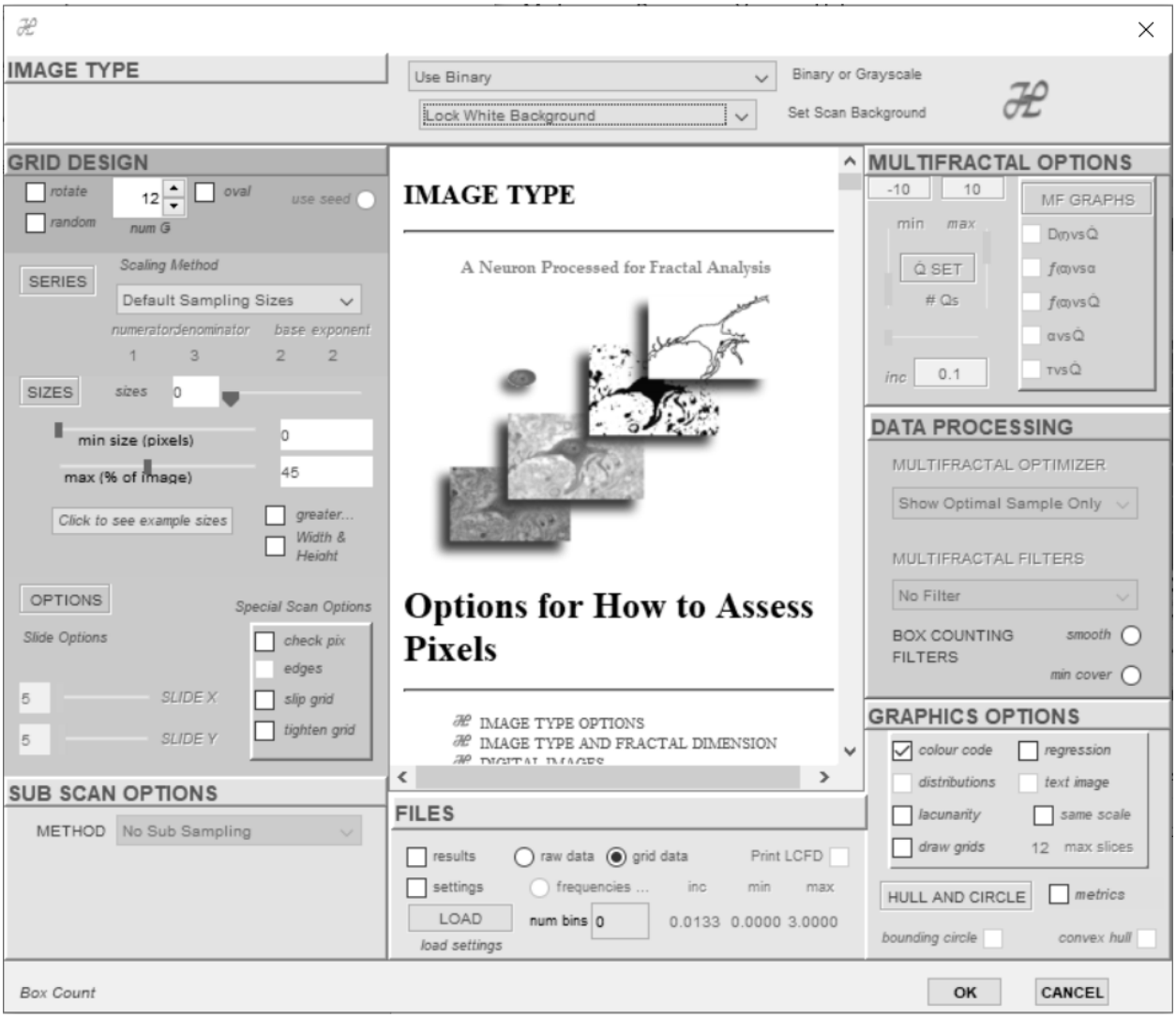

Figure 6. Default settings in FracLac for calculating box-counting dimension.

After the data were gathered, statistical tests were conducted to evaluate different categories of pattern and determine the statistical significance of the data.

Results

Several significant differences were found between the fractal dimensions of different types of blackwork patterns, between patterns designed or gathered by different authors, and between historical, modern, and historically-inspired patterns.

The first book of patterns analyzed was *The New Anchor Book of Blackwork Embroidery Stitches* (*The New Anchor Book*), edited by Cheryl Brown with all patterns and text by Jill Carter Nixon. This book was largely a how-to guide for blackwork embroidery. It contained instructions for basic stitches, advice on choosing threads and fabrics, and suggestions for displaying finished blackwork projects. The book also included 48 geometric filling patterns, 4 border patterns, and 16 patterns for more complicated projects, such as flowers or butterflies, utilizing the various filling patterns. Because the types of patterns could be broken into such distinct groups, a single-factor ANOVA was conducted on the fractal dimension data to see if there was a statistically significant difference between them. The resulting p-value of .079 was higher than the α of .05, indicating no statistically significant difference between the types of blackwork patterns in this book. As seen in Table 1, the mean fractal dimensions for all patterns fell between 1.8 and 1.9.

Table 1. Fractal dimensions of patterns in *The New Anchor Book*

Pattern Type	Number of Designs	Mean D_F
Fillings	48	1.801
Borders	4	1.881
Projects	16	1.847
Entire Book	68	1.817

Similar to *The New Anchor Book*, Becky Hogg's *Essential Stitch Guide: Blackwork* (ESG) provided an introduction to blackwork embroidery for beginners, offering lessons in

materials and stitching methods as well as instruction in more advanced techniques, such as shading with varying densities of pattern or thickness of thread. The book also provided 34 different filling patterns. The mean fractal dimension of these patterns was 1.861.

The next book analyzed was Lesley Wilkins's *Blackwork,* which included a brief introduction to the materials and techniques of sewing blackwork and a more detailed section guiding readers towards designing their own blackwork patterns from basic geometric shapes. Wilkins provided several pages of plant and animal motifs inspired by Medieval and Renaissance embroideries as well as hundreds of fill and border patterns. Because distinct groups could again be seen in the patterns provided, a single-factor ANOVA was conducted to determine if there was a statistically significant difference between the fractal dimensions of Wilkins's motifs, fillings, narrow borders, and wide borders. As compared to the α of .05, the resulting p-value of 5.79E-23 indicated there was at least one statistically significant difference between the groups. A Tukey-Kramer post hoc test revealed the differences between the following groups were statistically significant: motifs and narrow borders, motifs and wide borders, fillings and narrow borders, fillings and wide borders, and narrow borders and wide borders. As indicated in Table 2, the mean fractal dimensions of the motifs were close enough to be identical within three significant digits while the narrow borders and wide borders both had higher fractal dimensions on average.

Table 2. Fractal dimensions of patterns in Wilkins's *Blackwork*

Pattern Type	Number of Designs	Mean D_F
Motifs	52	1.846
Fillings	88	1.846
Narrow Borders	72	1.874
Wide Borders	18	1.901
Entire Book	230	1.859

Elisabeth Geddes and Moyra McNeil's *Blackwork Embroidery* was the next book analyzed and the first to delve deeper into the history of the craft. Nearly half of the book was devoted to a historical survey of Renaissance blackwork and the evolution of geometric patterns from Europe, Africa, and Asia that could have inspired blackwork. Though many of these patterns were illustrated in the book, they were not considered in this study, which was limited exclusively to patterns specifically designed for or executed via embroidery. A few blackwork patterns from Geddes and McNeil's historical survey were usable, specifically 10 that appeared as either drawings the authors had copied from historical sources or had photographed on flat cloth. While the book also included several portraits of people wearing embroidered clothing, these images were not included in this study because the patterns were warped by the drape and flow of the fabric. After the historical survey, Geddes and McNeil provided instructions for how the reader could design and sew their own blackwork embroidery. This section included 251 sewn or sketched patterns. As in other books, many of the patterns were fillings and borders, with a few more complicated projects provided for inspiration. Although these projects were stitched by a variety of artists, there was often no more than one project per artist, so the sample size was too small to compare the fractal dimension of artists within the book. Instead, a two-sample t-test was performed to compare the projects with the fill and border patterns, which were considered together because of the lack of clear differentiation in the book. The two-tailed p-value of .001 was less than the α of .05; therefore, there was a significant difference between the projects and the fillings and border patterns. The mean fractal dimensions of all patterns found in this book were lower than those that had been found elsewhere, as can be seen in Table 3. The historical blackwork patterns were not included in this analysis; they will be considered later.

Table 3. Fractal dimensions of patterns in *Blackwork Embroidery*

Pattern Type	Number of Designs	Mean D_F
Projects	26	1.747
Fillings and Borders	251	1.663
Entire Book	277	1.671

Two books by Ilse Altherr were analyzed in this study. The first, *Reversible Blackwork* (RB), was primarily another instruction guide to blackwork embroidery. It included information on materials, stitches, and project ideas, as well as a selection of 36 patterns and pathfinders for each to show the direction and order in which to make the stitches to achieve reversibility. The book also included as a frontispiece a single more complicated design stitched by the author. The mean fractal dimension of all the patterns excluding the frontispiece was 1.720.

The second book by Ilse Altherr, titled *Blackwork and Holbein Embroidery* (BHE), included 81 more patterns and accompanying pathfinders as well as 12 more complicated projects stitched by Altherr like the frontispiece of RB. According to Altherr, "A majority of the patterns, borders and medallions presented in this book were taken and graphed from historic samplers as they were found in textile study rooms throughout European museums;" thus, these patterns were considered examples of historical blackwork. The patterns were grouped into fillings, medallions, narrow borders, wide borders, and darning patterns. An ANOVA was conducted to look for differences between these groups as well as the more complicated project designs. As compared to an α of .05, the p-value of 3.51E-20 indicated a statistically significant difference between groups. According to a Tukey-Kramer post hoc test, the statistically significant differences lie between the following: complicated designs and fillings, complicated designs and medallions, complicated designs and narrow borders, fillings and medallions, fillings and narrow borders, medallions and wide borders, medallions and darning patterns, narrow

borders and wide borders, and narrow borders and darning patterns. As Table 4 shows, the mean fractal dimensions of the fillings, wide borders, and darning patterns were quite close as well as the highest in this book. The other kinds of patterns had lower fractal dimensions with narrow borders being the lowest.

Table 4. Fractal dimensions of patterns in BHE

Pattern Type	Number of Designs	Mean D_F
Projects	12	1.686
Fillings	34	1.760
Medallions	16	1.610
Narrow Borders	14	1.593
Wide Borders	5	1.759
Darning Patterns	12	1.745
Entire Book	93	1.697

Rosemary Drysdale's *The Art of Blackwork Embroidery* (ABE) was the next book of patterns analyzed. Like Geddes and McNeil's *Blackwork Embroidery*, this book began with a summary of the history of blackwork embroidery. No patterns were gathered from this section because all of the example embroideries pictured were also found in other sources. After discussing how readers can create blackwork embroideries of their own, Drysdale provided 45 filling patterns of her own design plus 6 more in a section entitled "Sources of Design." One of these patterns was a diagram of the pattern on the cuff of Jane Seymour in a portrait; the rest were based on architectural or natural features. Additionally, Drysdale provided 18 examples of blackwork projects, such as pillows, tablecloths, and eyeglasses cases. A two-sample t-test was conducted to determine if there was a statistically significant difference between the filling patterns, excluding the Jane Seymour cuff, and the projects provided in the book. As compared to an α of .05, the two-tailed p-value of 9.83E-13 indicated a statistically significant difference

between the projects and patterns. As can be observed in Table 5, the mean fractal dimension of the projects was higher than that of the filling patterns.

Table 5. Fractal dimensions of patterns in ABE

Pattern Type	Number of Designs	Mean D_F
Fillings	50	1.692
Projects	18	1.804
Entire Book	68	1.722

The final book considered in this study was Mary Gostelow's *Blackwork,* which contained the most examples of historical blackwork of all books examined. The first several chapters of the book presented a detailed study of the evolution of technique and symbolism of English blackwork on domestic and religious textiles, as depicted in court portraiture, and on garments preserved from the Renaissance era. Gostelow also surveyed blackwork created in other parts of Europe, Asia, America, and Africa. The book then explained the materials and stiches necessary for the reader to create their own blackwork and provided several examples of more modern blackwork pieces as inspiration and to illustrate the many sources of blackwork designs. While Gostelow provided samples of blackwork from different points across the sixteenth and seventeenth centuries, too few had definite dates to make any time-based groups within the Renaissance. The blackwork designs in this book were therefore divided into modern (post-1700) and historical (pre-1700) designs. A two-sample t-test was conducted to determine if there was a statistically significant difference between the groups. As compared to an α of .05, the two-tailed p-value of .331 indicated that there was no statistically significant difference present. As Table 6 illustrates, the mean fractal dimensions of both groups fell between 1.8 and 1.9.

Table 6. Fractal dimensions of patterns in Gostelow's *Blackwork*

Classification	Number of Designs	Mean D_F
Historical	22	1.828
Modern	55	1.843
Entire Book	77	1.838

After comparing the fractal dimensions of patterns within their source books, several comparisons were made of pattern groups drawn from across books. Because of the statistically significant differences found in many cases between filling, border, and larger project patterns, these were treated separately in comparisons of modern vs. historical blackwork. Patterns considered historical were made prior to the year 1700. To be considered modern, a pattern had to come from after 1700 and not claim direct inspiration from any historical source. Historically-inspired patterns were those made after 1700 and claiming to be inspired by Renaissance blackwork. The only book to contain historically-inspired patterns was Wilkins's *Blackwork*.

The first comparison was made between the fractal dimensions of modern filling patterns from across the books surveyed. A single-factor ANOVA was conducted on the 48 fillings from *The New Anchor Book*, the 34 fillings from ESG, the 226 fillings from *Blackwork Embroidery*, the 36 fillings from RB, and the 50 fillings from ABE. The resulting p-value of 1.25E-46 was lower than the α of .05, indicating a statistically significant difference between the groups. A Tukey-Kramer post hoc test revealed that the significant differences lay between every combination of groups except RB and ABE. As can be seen in Table 7, patterns from these two books had fractal dimensions just above and just below 1.7 while the others were significantly greater or less than 1.7. RB and ABE were grouped together for subsequent analyses because of the lack of significant difference.

Table 7. Fractal dimensions of modern filling patterns

Title	Classification	Number of Designs	Mean D_F
The New Anchor Book	Modern	46	1.801
ESG	Modern	34	1.861
Blackwork Embroidery	Modern	225	1.661
RB	Modern	36	1.720
ABE	Modern	50	1.692

The next comparison made was between modern and historical blackwork filling patterns. A series of two-sample t-tests was performed comparing each set of filling patterns from *The New Anchor Book*, ESG, *Blackwork Embroidery*, and RB and ABE together with the historical filling patterns from BHE. A statistically significant difference was present between all groups, as can be seen from the α and p-values reported in Table 8. The mean fractal dimension of the patterns from BHE was 1.760. As Table 8 also illustrates, two of the books contained patterns with fractal dimensions greater than that value and two contained patterns with fractal dimensions lower than it.

Table 8. Fractal dimensions of modern filling patterns compared to historical patterns from BHE (mean $D_F = 1.760$)

Title	Classification	Number of Designs	Mean D_F	Two-tailed p-value	α	Statistically Significant?
The New Anchor Book	Modern	46	1.801	.011	.05	yes
ESG	Modern	34	1.861	1.81E-19	.05	yes
Blackwork Embroidery	Modern	225	1.661	1.39E-21	.05	yes
RB and ABE	Modern	86	1.704	2.46E-08	.05	yes

Next, another series of two-sample t-tests was performed comparing each of the modern sets of filling patterns and the historical filling patterns to the historically-inspired filling patterns and motifs from Wilkins's *Blackwork*. As reported in Table 9 below, there was a statistically significant difference between all groups. All mean fractal dimensions of the patterns were lower than the that of the historically-inspired patterns in Wilkins's *Blackwork* except for those in ESG, which had a higher mean fractal dimension.

Table 9. Fractal dimensions of modern filling patterns and historical patterns compared to historically-inspired patterns from Wilkins's *Blackwork* (mean $D_F = 1.846$)

Title	Classification	Number of Designs	Mean D_F	Two-tailed p-value	α	Statistically Significant?
The New Anchor Book	Modern	46	1.801	.004	.05	yes
ESG	Modern	34	1.861	7.61E-6	.05	yes
Blackwork Embroidery	Modern	225	1.661	2.6E-100	.05	yes
RB and ABE	Modern	86	1.704	4.96E-35	.05	yes
BHE	Historical	88	1.760	1.75E-17	.05	yes

Borders were the next kind of pattern considered. In the data gathered, there were 4 modern border patterns from *The New Anchor Book*, 73 historically-inspired narrow border patterns and 18 wide border patterns from Wilkins's *Blackwork*, 14 historical narrow border patterns and 5 wide border patterns from BHE, and one wide border pattern (the Seymour cuff) from ABE. The modern border patterns in *The New Anchor Book* were much more like the narrow borders reported elsewhere in design; therefore, a single-factor ANOVA was conducted comparing them to the historical and historically-inspired narrow border patterns. The resulting p-value of 3.55E-62 was lower than the α of .05, indicating a statistically significant difference between the groups. A Tukey-Kramer post hoc test revealed that the statistically significant

difference lay between the historically-inspired and historical designs. As can be seen in Table 10, the historical border patterns from BHE had a much lower fractal dimension than the modern and historically-inspired patterns from the other two books.

Table 10. Fractal dimensions of narrow border patterns

Title	Classification	Number of Designs	Mean D_F
The New Anchor Book	Modern	4	1.881
Blackwork (Wilkins)	Historically-inspired	73	1.874
BHE	Historical	14	1.593

A two-sample t-test was conducted to compare the fractal dimensions of the historically-inspired wide border patterns from Wilkins's *Blackwork* and the historical wide border patterns, including the 5 from BHE and the Seymour cuff pattern from ABE. As compared to the α of .05, the resulting p-value of 3.31E-4 indicated a statistically significant difference between the groups. As can be seen in Table 11, the mean fractal dimension of the historically-inspired patterns was higher than that of the historical patterns.

Table 11. Fractal dimensions of wide border patterns

Title	Classification	Number of Designs	Mean D_F
Blackwork (Wilkins)	Historically-inspired	18	1.901
BHE	Historical	6	1.753

After comparing border patterns, comparisons were made between the modern and historical patterns for more complicated projects. These included 16 modern patterns from *The New Anchor Book,* 26 modern patterns and 10 historical patterns from *Blackwork Embroidery*,

13 modern patterns from RB and BHE, 18 modern patterns from ABE, and 22 historical and 55 modern patterns from Gostelow's *Blackwork.* A single-factor ANOVA was conducted to compare the modern patterns. As compared to the α of .05, the two-tailed p-value of 9.7E-14 indicated a statistically significant difference between the groups. A Tukey-Kramer post hoc test revealed that the differences lay between *The New Anchor Book* and *Blackwork Embroidery*, *The New Anchor Book* and RB and BHE, *Blackwork Embroidery* and ABE, *Blackwork Embroidery* and Gostelow's *Blackwork,* RB and BHE and ABE, and RB and BHE and Gostelow's *Blackwork*. Because no significant difference lay between *The New Anchor Book*, *ABE*, and Gostelow's *Blackwork,* as can be seen in Table 12, these designs were considered together in subsequent analyses.

Table 12. Fractal dimensions of modern project patterns

Title	Classification	Number of Designs	Mean D_F
The New Anchor Book	Modern	16	1.847
Blackwork Embroidery	Modern	26	1.747
RB and BHE	Modern	13	1.689
ABE	Modern	18	1.804
Gostelow's *Blackwork*	Modern	55	1.843

The next comparison made was between the historical patterns in *Blackwork Embroidery* and Gostelow's *Blackwork*. A two-sample t-test was conducted on the data. The two-tailed p-value of .015 was lower than the α of .05, indicating a statistically significant difference between the groups. As can be seen in Table 13, the patterns in Gostelow's *Blackwork* had a higher mean fractal dimension.

Table 13. Fractal dimensions of historical project patterns

Title	Classification	Number of Designs	Mean D_F
Blackwork Embroidery	Historical	10	1.741
Gostelow's *Blackwork*	Historical	22	1.828

Next, comparisons were made between the modern and historical designs. A series of two-sample t-tests was conducted comparing each group of modern designs to the historical designs found in *Blackwork Embroidery*. As reported below in Table 14, the only statistically significant difference lay between the historical designs and modern designs found in *The New Anchor Book*, ABE, and Gostelow's *Blackwork*.

Table 14. Fractal dimensions of historical project patterns compared to historical patterns from *Blackwork Embroidery*

Title	Classification	Number of Designs	Mean D_F	Two-tailed p-value	α	Statistically Significant?
The New Anchor Book, ABE, and Gostelow's *Blackwork*	Modern	89	1.836	.009	.05	yes
Blackwork Embroidery	Modern	26	1.747	.888	.05	no
RB and ABE	Modern	13	1.689	.139	.05	no

Another series of two-sample t-tests was conducted comparing each group of modern designs to the historical designs found in Gostelow's *Blackwork*. As Table 15 shows, two statistically significant differences were found: between *Blackwork Embroidery* and Gostelow's *Blackwork* and between RB and ABE and Gostelow's *Blackwork*.

Table 15. Fractal dimensions of historical project patterns compared to historical patterns from Gostelow's *Blackwork*

Title	Classification	Number of Designs	Mean D_F	Two-tailed p-value	α	Statistically Significant?
The New Anchor Book, ABE, and Gostelow's *Blackwork*	Modern	89	1.836	.594	.05	no
Blackwork Embroidery	Modern	26	1.747	.003	.05	yes
RB and ABE	Modern	13	1.689	1.13E-5	.05	yes

Two comparisons were made considering all patterns in the study. A single-factor ANOVA was conducted on the fractal dimensions of all patterns that fell into the following groups: fillings, narrow borders, wide borders, and complete projects. As compared to the α of .05, the p-value of 2.33E-28 indicated a statistically significant difference between the groups. A Tukey-Kramer post hoc test was conducted, and differences of statistical significance were found to be between all groups except narrow borders and wide borders and between narrow borders and complete projects. Table 16 reports the total means for each category and the means divided by books.

Table 16. Mean fractal dimensions of fillings, narrow borders, wide borders, and complete projects across books surveyed

Title	Classification	Fillings	Narrow Borders	Wide Borders	Complete Projects
The New Anchor Book	Modern	1.801	1.881		1.847
ESG	Modern	1.861			
Wilkins's *Blackwork*	Historically-inspired	1.846	1.874	1.901	
Blackwork Embroidery	Modern	1.663			1.747
Blackwork Embroidery	Historical				1.741
RB	Modern	1.720			
BHE	Modern				1.686
BHE	Historical	1.760	1.593	1.759	
ABE	Modern	1.692			1.804
ABE	Historical			1.7205	
Gostelow's *Blackwork*	Modern				1.843
Gostelow's *Blackwork*	Historical				1.828
Total		1.733	1.831	1.864	1.803

Finally, a single-factor ANOVA was conducted on all patterns that could be categorized as historical, modern, or historically-inspired. There was a statistically significant difference between the groups because the resulting p-value of 2.3E-63 was lower than the α of .05, and a Tukey-Kramer post hoc test revealed that the significant differences lay between the modern and historically-inspired patterns and between the historical and historically-inspired patterns but not between the historical and modern patterns. As can be seen in Table 17, the historically-inspired patterns had a higher mean fractal dimension.

Table 17. Fractal dimensions of historical, modern, and historically-inspired patterns across books surveyed

Classification	Mean D_F
Historical	1.728
Modern	1.731
Historically-inspired	1.859

Discussions and Conclusions

The purpose of this study was to examine data on the fractal dimensions of historical, modern, and historically-inspired blackwork embroidery and search for trends that could be used to evaluate historical accuracy. Comparisons of various groups indicated statistically significant differences between different types of blackwork patterns and between patterns designed or collected by various authors. However, when the data were taken as a whole, there were no statistically significant differences between modern and Renaissance-era blackwork patterns. This suggests that, if fractal dimension is to be used to evaluate historical accuracy, the type of pattern must also be taken into account.

Historical filling patterns had a mean fractal dimension of 1.760, and the means of modern filling patterns fell above and below that number. Historical narrow border patterns had a mean fractal dimension of 1.593, which was lower than both modern and historically-inspired patterns. The mean fractal dimension of historical wide border patterns was 1.753, which was lower than the mean of the historically-inspired wide border patterns. When considering the fractal dimensions of patterns for complete projects, a statistically significant difference was found between the two books that contained historical designs, *Blackwork Embroidery* and Gostelow's *Blackwork*. The means of the fractal dimensions of the patterns of these two books were 1.741 and 1.828, respectively. The means of the fractal dimensions for modern patterns fell above and below both values. Interestingly, three of the five mean fractal dimensions associated with historical blackwork embroidery patterns fell close to 1.75. Upon examination of the patterns that produced these numbers, it was noted that the historical filling patterns and wide border patterns from BHE and the patterns from *Blackwork Embroidery* tended to be around the same size or appear as if they would take around the same amount of space when stitched;

moreover, the historical patterns in *Blackwork Embroidery* were often samples of larger patterns from illustrations (Figure 7). The patterns pictured in Gostelow's *Blackwork* tended to fill larger areas, like the coif pictured in Figure 8. If this difference in the scale of the pattern is the reason for the higher fractal dimensions calculated for the patterns from this source, then it can be concluded from this data that the fractal dimensions of Renaissance-era blackwork patterns tend to fall near 1.75, save in the case of narrow borders, which have fractal dimensions around 1.59.

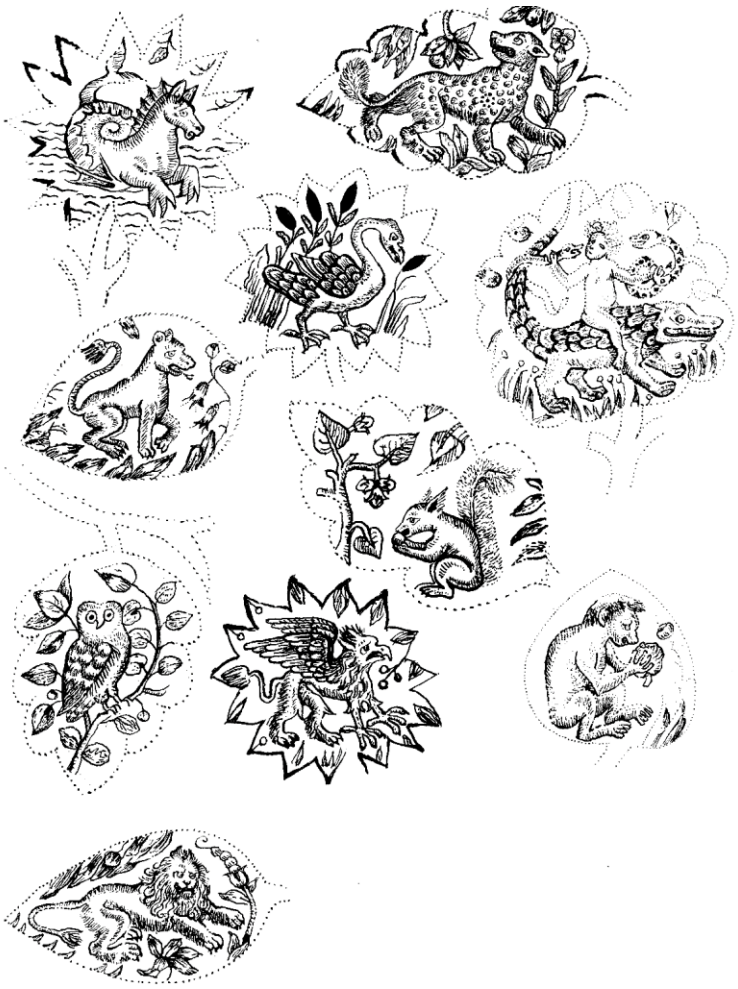

Figure 7. Motifs from the Falkland Tunic as pictured in *Blackwork Embroidery*. Edited by author for fractal analysis.

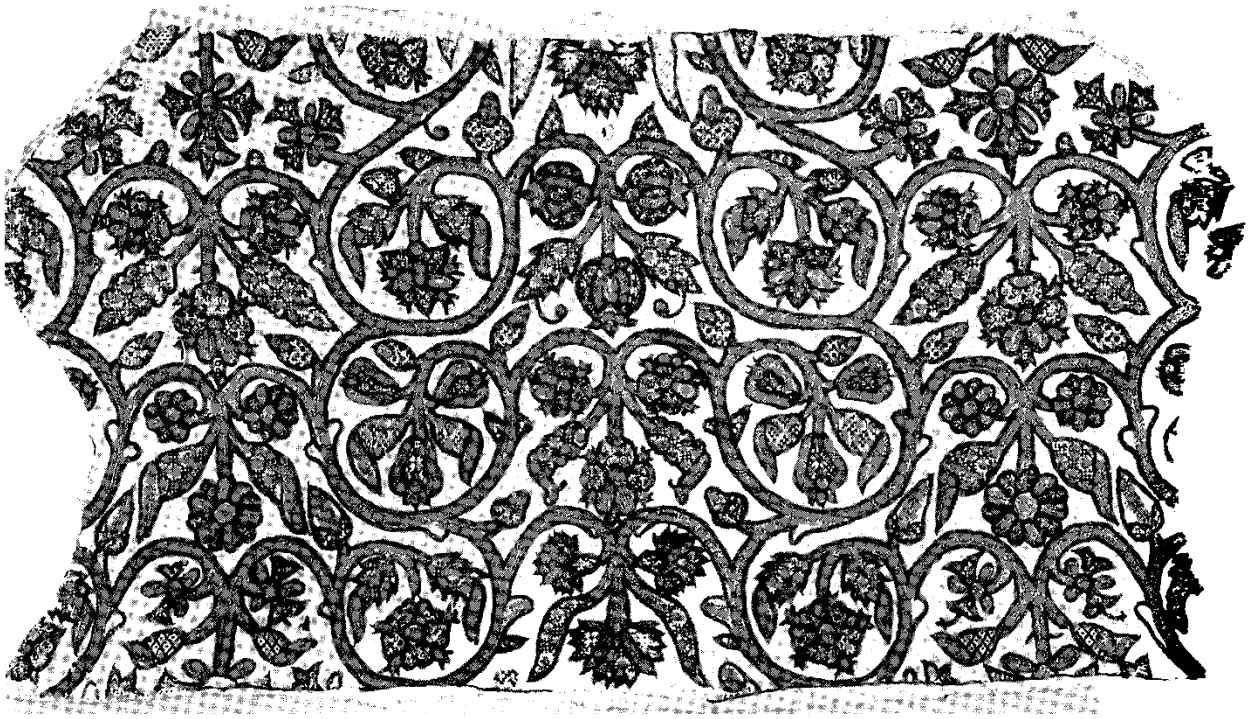

Figure 8. Sixteenth- or seventeenth-century coif as pictured in Gostelow's *Blackwork*. Edited by author for fractal analysis.

The historically-inspired patterns found in Wilkin's *Blackwork* all had mean fractal dimensions higher than 1.75 and even higher than 1.828, the highest mean fractal dimension seen among the historical designs. This suggests that, despite being inspired by patterns such as those found in Figures 7 and 8, Wilkins took the artistic liberty to design more complex designs. It is possible also that Wilkins increased the complexity of the designs unintentionally. As can be seen in Figure 9, which compares one of Wilkins's patterns ($D_F = 1.835$) with the Seymour cuff ($D_F = 1.7205$), such small differences in fractal dimension may be difficult for the human eye to observe.

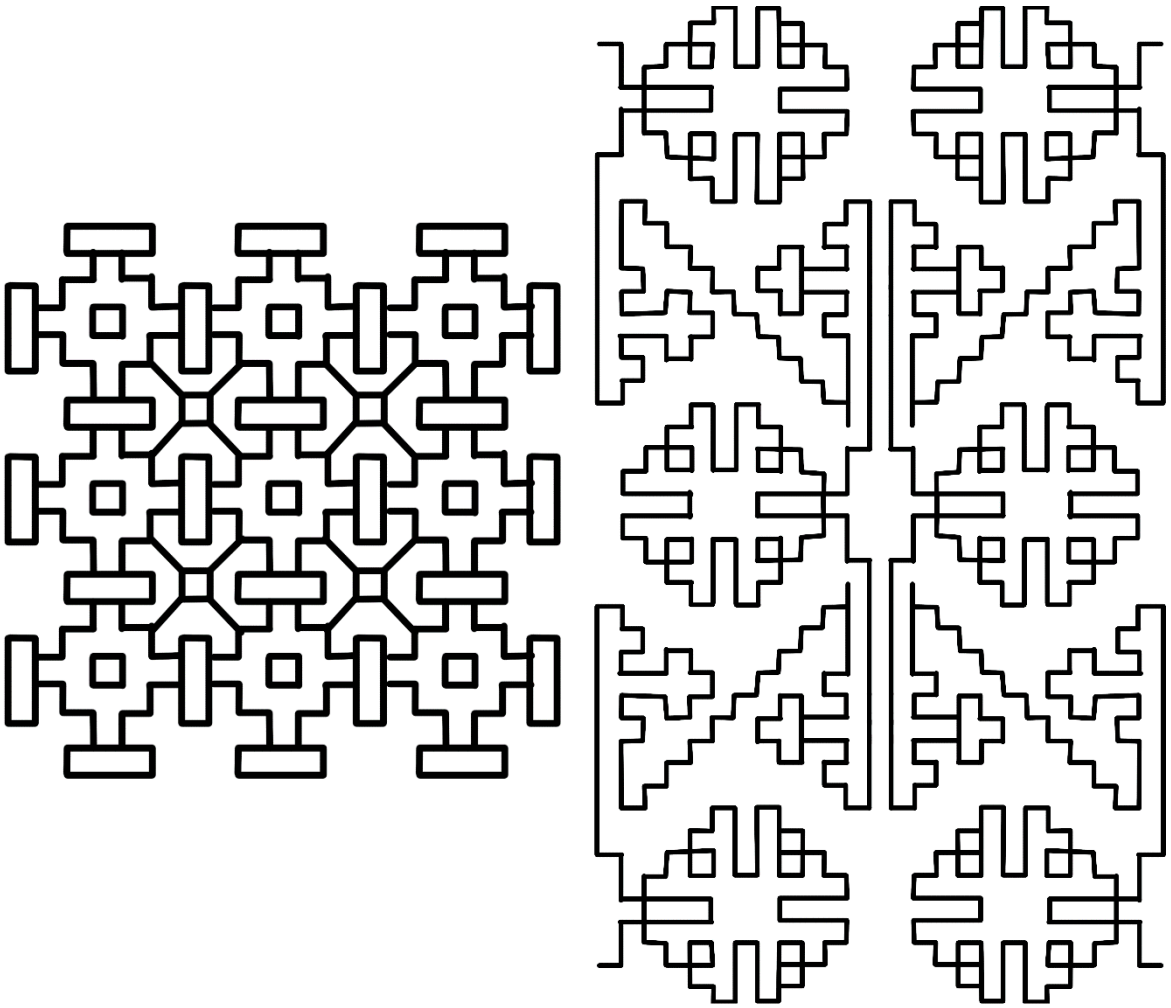

Figure 9. A fill pattern from Wilkins's *Blackwork* and the Seymour cuff pattern from ABE. Edited by author for fractal analysis.

The modern blackwork patterns with fractal dimensions closest to the historical patterns from *Blackwork Embroidery* were the modern patterns from *Blackwork Embroidery* and from RB and BHE, as no statistically significant difference existed between the means of these groups.

When comparing the appearances of modern versus historical blackwork patterns, it becomes apparent that having a similar fractal dimension does not necessarily equate to visual similarity. Figure 10 shows a comparison of two patterns from *Blackwork Embroidery*, a historical pattern and a modern pattern, with fractal dimensions of 1.748 and 1.731, respectively. Despite these designs' proximity to each other in terms of visual complexity, there are clear

stylistic differences. The lines of the Renaissance design are flowing and organic, the looping shape of the plants reflected at a smaller scale in the round segments of the pods or flowers. The train design, on the other hand, contains hardly any curvilinear lines save the curl of the smoke. Even the wheels are octagonal, not round. The zigzagging and crosshatching that fills the train cars is reminiscent of the overall rectangular and slanted design of the vehicle. In addition to the obvious fact that trains like this did not exist in the Renaissance, it is clear that the designs are examples of different styles.

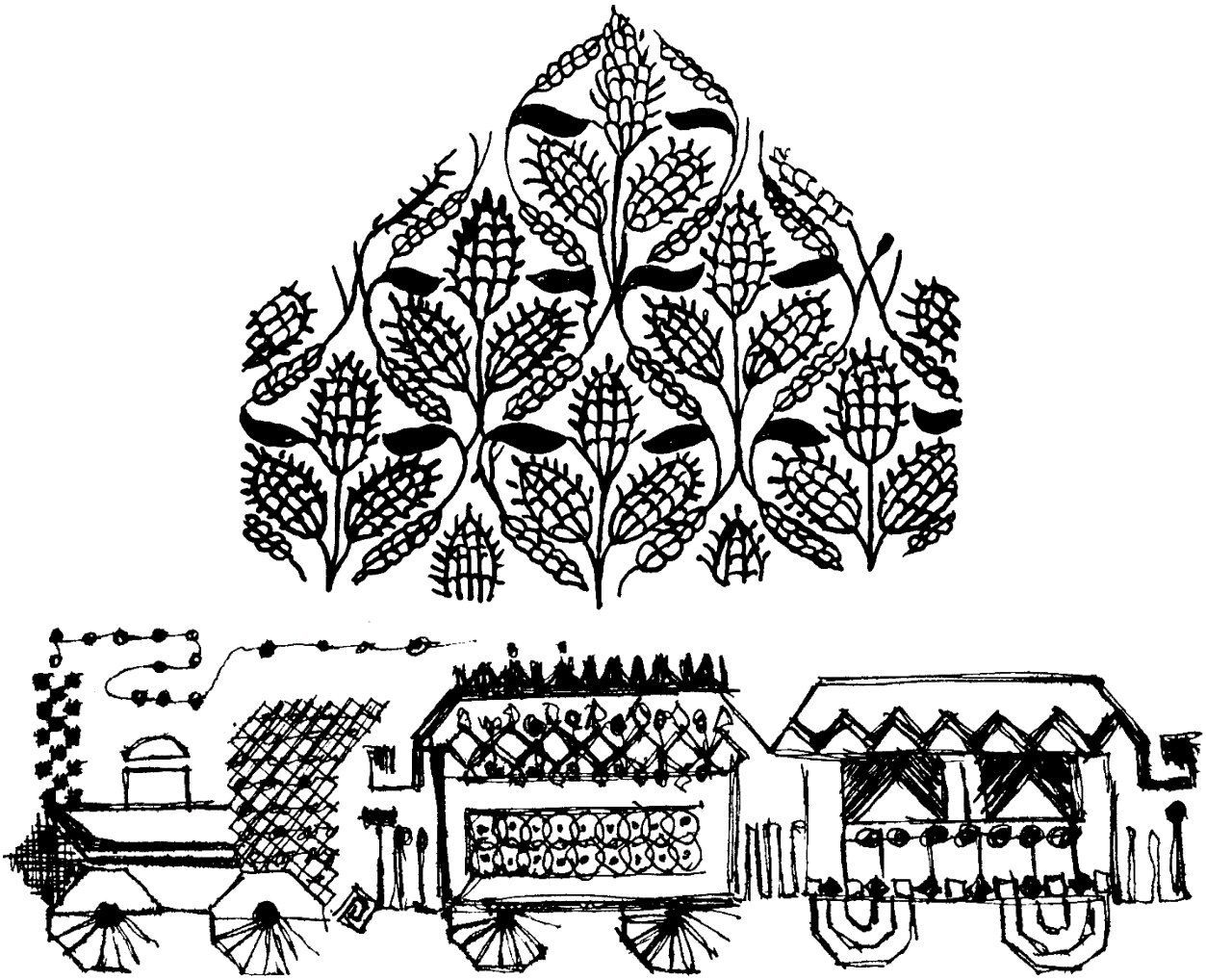

Figure 10. Historical pattern (top) and modern pattern (bottom) from *Blackwork Embroidery*. Edited by author for fractal analysis.

Though Altherr made no claim that the patterns and samples of large projects featured in RB and BHE were inspired by the historical patterns featured elsewhere in the book, it is possible that they were, even if not consciously, which could explain their closeness in fractal dimension to historical patterns. Figure 11 illustrates a sample of Altherr's work. Like the Renaissance design from *Blackwork Embroidery* depicted in Figure 10, Altherr's embroidery incorporates scrolling floral designs and a limited approximation of self-similarity in the way the leaves form a downwards curve much like their own shapes.

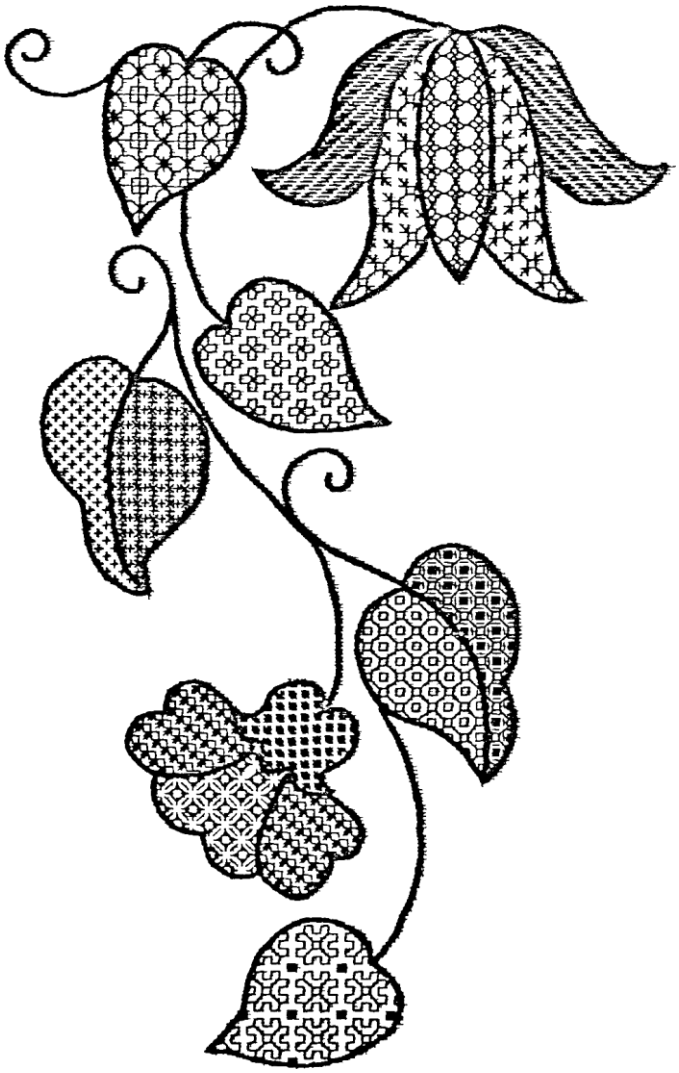

Figure 11. Modern project pattern from BHE. Edited by author for fractal analysis.

In addition to comparing historical and modern blackwork patterns, this study compared the different types of blackwork pattern found in the books. There were often, but not always, statistically significant differences between the fractal dimensions of patterns for borders, fillings, and complete projects. Overall, complete projects tended to have higher fractal dimensions than filling patterns, and narrow and wide borders tended to have higher fractal dimensions than both. That blackwork projects have higher fractal dimensions than blackwork fillings is logical, as fillings are often constituent parts of projects. However, it seems strange that border patterns would be more complex than patterns for larger projects. Though many of the projects incorporated the filling patterns found in the books, few incorporated the borders. Perhaps this reflects an intention for the border designs to stand on their own rather than being part of a larger picture, as earlier Renaissance patterns did on collars and cuffs. The higher complexity of the borders may be a way of compensating for the lack of visual interest on the rest of the garment or image.

Overall, the fractal dimensions of the blackwork patterns considered in this study were relatively high. Most fell into the range 1.7 to 1.9. The lowest value recorded was 1.512 and the highest value recorded was 1.908. Not a single pattern fell into the range 1.3 to 1.5 reported by many studies to be the fractal dimension range of greatest human preference.[36] This could indicate several things. Perhaps the fractal dimension range of greatest human preference was higher in the past, or perhaps being outside this range was the reason blackwork embroidery never gained more popularity than it did. Further research into this subject could involve calculating the fractal dimensions of other samples of Renaissance art and comparing it to the

36. Spehar, "Universal Aesthetic of Fractals;" Street, "A Complex Story';" Taylor, "Perceptual and Psychological Responses."

fractal dimensions of modern art. Moreover, the findings of Bies et al. suggest that, when considering exact fractals, study participants prefer images with higher complexities.[37] Because of their geometric and linear nature, blackwork patterns may evoke perceptual responses more like these exact fractals than the abstract paintings or scenes of nature considered in other studies.

Many blackwork patterns considered in this study depicted leaves, vines, flowers, birds, and other details reminiscent of nature. Studies suggest that the appeal of complex fractal designs may be associated with their proximity to the complexity of natural scenes.[38] It would be interesting to compare the fractal dimensions of these patterns to actual natural scenes, particularly those depicting dense foliage. Additionally, a trend of declining natural motifs was noted in the patterns surveyed. Renaissance patterns, like that depicted in Figure 12, were often full of plants and animals, while modern patterns tended to depict nonorganic, particularly architectural, features, like those seen in Figure 13. This trend may reflect the increase in urbanization over the past few centuries on the art of blackwork. As embroiderers' surroundings changed, so did the style and subject matter of their artwork. Perhaps the use of nature-like fills in blackwork patterns depicting inorganic forms reflects a desire to make perception of these forms more visually interesting and more like perception of nature.

37. Bies, "Aesthetic Responses to Exact Fractals."

38. Taylor, Micolich, and Jonas, "Fractal Expressionism."

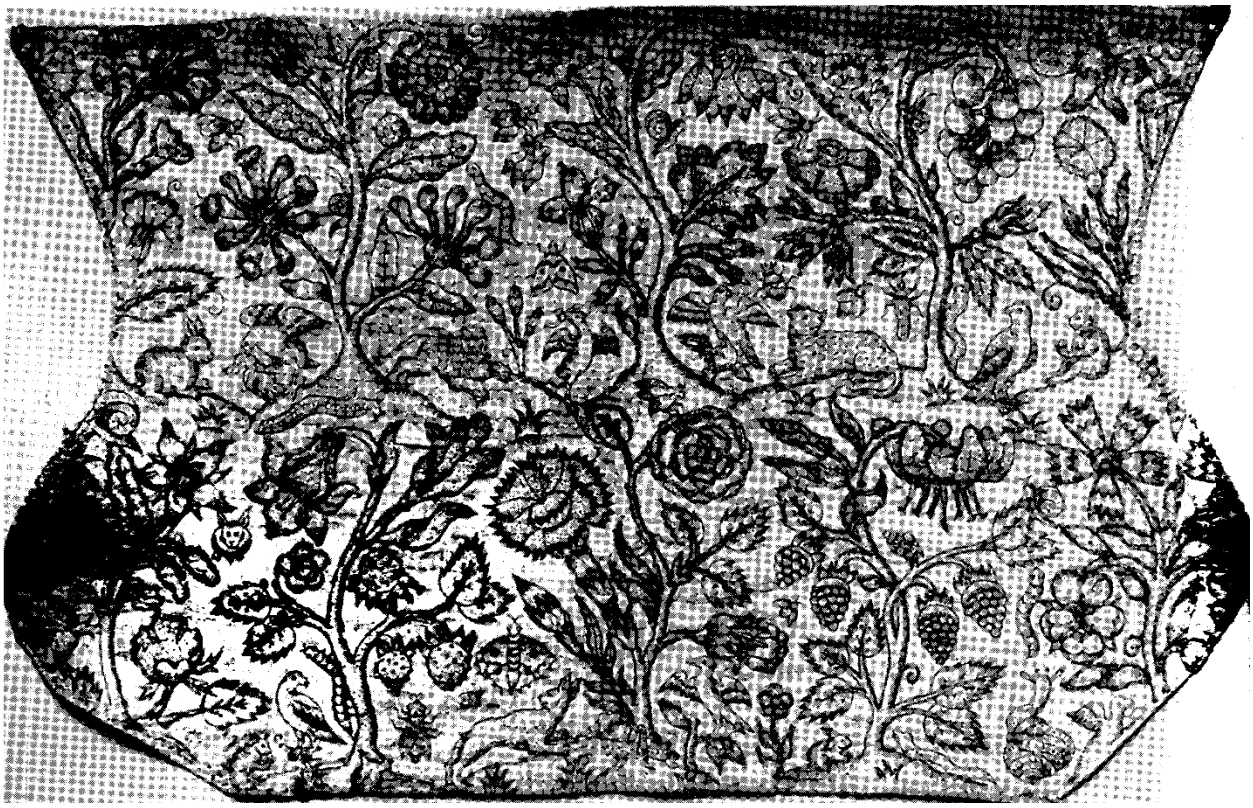

Figure 12. Sixteenth- or seventeenth-century coif as pictured in Gostelow's *Blackwork* depicting a great variety of flora and fauna. Edited by author for fractal analysis.

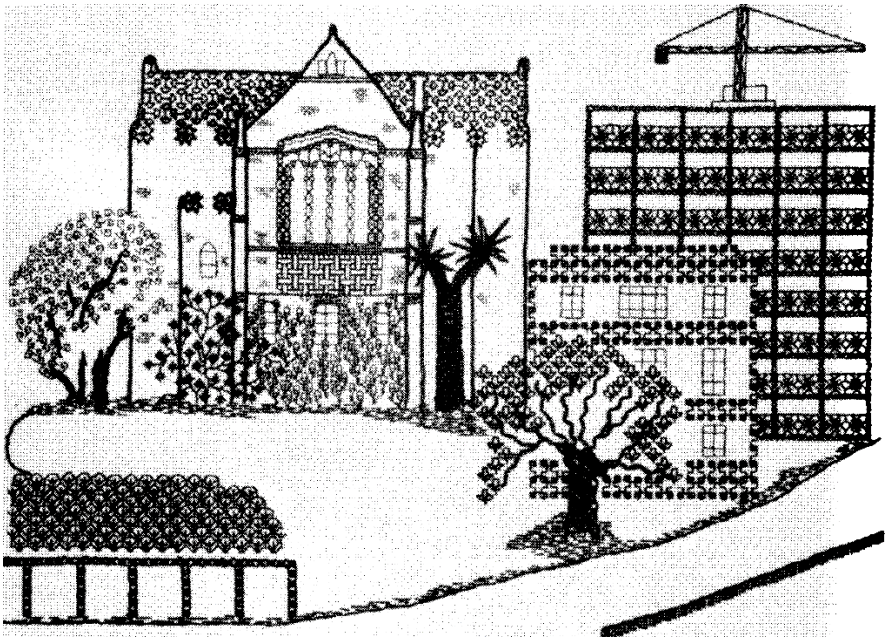

Figure 13. Modern Blackwork pattern from Gostelow's *Blackwork* showing architectural inspiration. Edited by author for fractal analysis.

Another trend noted in the patterns studied was a shift in the purpose of blackwork embroidery. In the Renaissance, the most common use of blackwork was in fashion; however, there are hardly any examples of modern blackwork used for such a purpose. Rather, modern blackwork designs tend to be presented on linens, pillows, or wall hangings, where they are the only decoration on the item. In contrast, blackwork appearing on extravagant Renaissance clothing was often not the only form of decoration; it frequently appeared in tandem with rich fabrics, jewels, spangles, lace, and other forms of embroidery. Further research could consider how the complexity of blackwork patterns relates to the complexity of the overall outfit.

There are numerous other ways in which fractal analysis could be used to further study blackwork embroidery. If more samples of historical blackwork can be found, it may be possible to identify changes in fractal dimension that reflect the shift from geometric Spanysshe work to floral designs within the Renaissance era. Specific motifs appearing in patterns, such as crosses or Celtic knots could be analyzed to determine if there is a fractal dimension at which they are typically depicted. With more samples of historical blackwork, it may also be possible to examine how factors like the use of an embroidered garment or the social class of its owner relate to fractal dimension. Any form of blackwork, not only historical patterns, can be examined to see how the fractal dimensions of the various filling patterns used relate to the overall fractal dimension of the design. Further research could examine whether the overall outline of the design functions like the anchor layers of Jackson Pollock's paintings observed by Taylor, Micolich, and Jonas,[39] or whether the fractal dimension of the filling pattern is the chief factor in determining the complexity of the overall design.

39. Taylor, Micolich, and Jonas, "The Construction of Jackson Pollock's Fractal Drip Paintings."

Fractal analysis is a field of study that combines mathematics, computer science, and perceptual studies, allowing a deeper understand of the patterns and forms visible in the world than simply what we can see. Fractal analysis of art provides a means of studying the complexity of designs that defy other forms of classification, and the objective metric of fractal dimension allows for many practical applications.

More research is necessary to develop exact parameters that could be used to determine the historical accuracy of a blackwork design, though the proximity of many designs in this study to 1.75 may be a good starting point. Further studies could examine additional blackwork patterns from the Renaissance and attempt to establish a range in which the fractal dimensions of historical patterns typically fall. In future studies, it may be beneficial to mitigate the confounding variable of scale by limiting and standardizing the size of the pattern sampled by, for example, considering only five-centimeter squares of patterns that cover larger areas of fabric. As the comparison of modern and historical patterns from *Blackwork Embroidery* seen in Figure 10 makes clear, the overall form and subject matter of a pattern must be considered in addition to the fractal dimension. While the fractal dimension of a pattern may be one factor to consider when evaluating historical accuracy, it is not the only factor, and the process of determining the historical accuracy of a blackwork pattern is, like the patterns themselves, quite complex.

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