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# Stereoscopic comparison as the long-lost secret to microscopically detailed illumination like the *Book of Kells*'

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**Abstract.** The idea that the seventh- and eighth-century illuminators of the finest few Insular manuscripts had a working knowledge of stereoscopic images (otherwise an eighteenth- and nineteenth-century discovery) helps explain how they could create singularly intricate, microscopically detailed designs at least five centuries before the earliest known artificial lenses of even spectacle quality. An important clue to this long-standing problem is that interlace patterns drawn largely freehand in lines spaced as closely as several per millimeter repeat so exactly across whole pages that repetitions can be free-fused to form microscopically detailed stereoscopic images whose relief in some instances indicates precision unsurpassed in astronomical instruments until the Renaissance. Spacings between repetitions commonly harmonize closely enough with normal interpupillary distances that copying disparities can be magnified tens of times in the stereoscopic relief of the images. The proposed explanation: to copy a design, create a pattern, or perfect a design's template, the finest illuminators worked by successive approximation, using their presumably unaided eyes first as a camera lucida to fill a measured grid with multiple copies from a design, and then as a stereocomparator to detect and minimize disparities between repetitions by minimizing the relief of stereoscopic images, in the manner of a Howard – Dolman stereoacuity test done in reverse.

## 1 Introduction

This paper makes a case that stereoscopic imagery was known a millennium before the first published reports of the eighteenth and nineteenth centuries (see Howard and Rogers 1995, page 43; Wade 1998, page 301). It proposes that free-fusion stereocomparison is the answer to the long-standing question of how certain particularly gifted artists of the early medieval British Isles were able to illuminate the finest manuscripts of the Insular type in microscopic detail centuries before the earliest known magnifying lenses of even spectacle quality became available (section 2.1). As it turns out, these primary examples—the *Book of Durrow* (~670 – 680 AD), *Lindisfarne Gospels* (~700–720 AD), and *Book of Kells* (~800 AD)—are associated exclusively with a family of monasteries founded by a famous scribe known for reputed miracles of rapid proofreading reminiscent of what present-day proofreaders can achieve by free-fusion stereocomparison (section 5.1, table 1).

The major points of the argument are, first, that a novel twist on a now well-known trick of free-fusion stereoscopic viewing would have enabled the artists to achieve the magnification of errors needed to work in microscopic detail, but only in the context of repeating patterns such as characteristic of Insular illumination (section 2.2); second, that the viewing trick is the only apparent means by which a normally sighted artist could have achieved sufficiently high magnification, given the technology of the time (section 2.3); third, that a specific set of procedures for using this trick should have sufficed to create the illumination in question, including templates for the designs (sections 3.1 – 3.4); and fourth, that Insular illumination of the finest quality shows definite signs of having been created with the hypothesized technique, whereas typical examples in the remaining 80-odd Insular manuscripts do not (section 4).

## 2 Background

### 2.1 *The 'micrography problem' in Insular illumination*

The finest Insular manuscripts have long been famous for their singularly intricate, technically astonishing, microscopically detailed illumination (Alexander 1978). Though much has been written about how Insular interlace was laid out (for instance, Allen 1903; Bain 1951; Hull 2003), little has been devoted to the practical problem of interest here: how it was rendered in microscopic detail. A centimeter-long pin dropped onto one of the more richly illuminated pages in the *Book of Kells* could cross 30 or more exquisitely fine lines, or almost as many as it could on the counterfeit-resistant engraving on a US $1 bill, and could cross as many as 15 – 20 in the *Lindisfarne Gospels* and 10 – 15 in the *Book of Durrow*. Though glass-bead and water-drop lenses were known in antiquity, and have been related to ancient micrographic inscriptions and gem engravings (for instance, Hogg 1858, pages 1 – 3; Brumbaugh 1966, pages 16 – 19), there is no precedent for work of comparable intricacy on the scale of a manuscript page. Though spectacle-quality magnifying lenses were being made as early as 1286 (Angus-Butterworth 1957, page 230; Bischoff 1990, page 19; Wade 1998, page 50; the suggestion by Van Stone 1994, page 241, notwithstanding), illumination of a delicacy comparable to that in the finest Insular manuscripts is not seen again until the finest Books of Hours of the fifteenth and sixteenth centuries, such as the Duke of Berry's *Très Riches Heures* ($\sim$1413 – 1489; 15 – 20 lines $cm^{-1}$; see Longnon et al 1969). By that time illuminators were picturing themselves at work with spectacles and large magnifying glasses (Alexander 1992, pages 4 – 34; de Hamel 1992, pages 27 – 70).

Art historians have been at a loss to explain how a small and isolated group of early medieval artists in the northern British Isles could have worked in such precision centuries in advance of contemporary technology. What is here called the 'micrography problem' was recognized very early: Giraldus Cambrensis, a widely traveled twelfth-century Anglo-Welsh scholar, must have seen hundreds of manuscripts illuminated in many styles before he encountered one near Kells in Ireland which seemed to him so far beyond contemporary technical capabilities that he believed it must be "the work not of men but of angels" (O'Meara 1951, page 67). Rupert Bruce-Mitford, who reconstructed the process of the Lindisfarne Gospels' illumination from surviving toolmarks and guidelines for the 1956 – 1960 facsimile edition, concluded that "behind the perfection of [the] ornamental work lies ... a perfected system of minute measurement and a most accomplished geometry, implying the use of delicate and highly efficient tools" (Brown and Bruce-Mitford 1960b, page 291). There is no question about the sophistication of the geometry (Hull 2003), but the only tools for which there is archaeological or other evidence are various forms of stylus, compass, straight edge, and dividers (Backhouse 1981, pages 28 – 31; Brown 2003, pages 214 – 226, 291 – 296). What is more, such tools evidently were used only to draft the guidelines; the details themselves were added freehand (Brown and Bruce-Mitford 1960b, pages 109 – 260; Brown 2003, page 291).

A first clue to the micrography problem is that the most intricate designs often occur in the context of regularly repeating patterns, as in figure 1 (hereafter the word 'pattern' will be used in the restricted sense of ornament formed by symmetrical repetition of a design). The Insular style of ornament is characterized by singularly intricate geometric designs and patterns. Of particular interest here is interlace, which commonly contains curves too complex to be rendered entirely with compass and straightedge (see figure 1). Designs and patterns resembling knots, braids, woven mats, and carpets apparently adapted from the fiber arts are found carved on stone monuments, inlaid or chip-carved in jewelry, and braided in gold wire as little as 100 μm thick in the filigree on the finest pieces of metalwork, such as the Hunterston and Tara Brooches (for instance, Whitfield 1993, 2007). Later, as Christianity, the book, the written

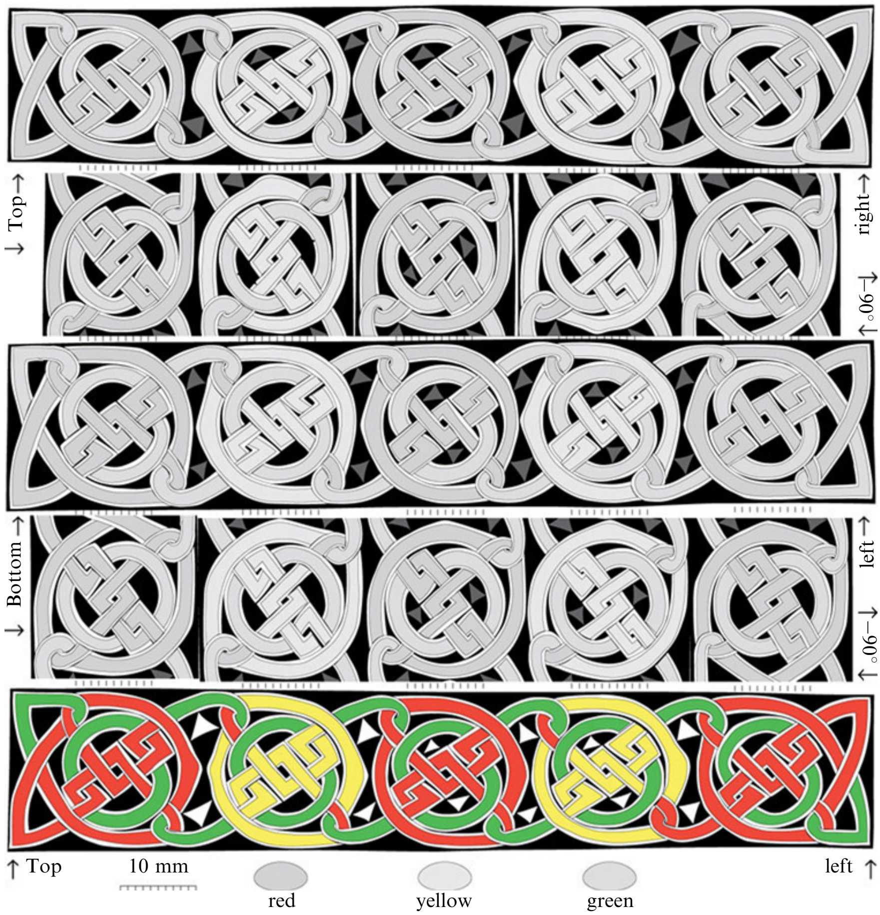


**Figure 1.** Interlace of the Insular style on the top and bottom panels of folio 191v in the *Book of Durrow* (~670–680 AD), illustrating how corresponding parts of the five roundels have been copied so accurately that they can be stereoscopically fused with the unaided eyes at normal reading distances. Colors in all but the lowest panel are shown in barely distinguishable shades of gray so that luminance will interfere minimally with stereocomparison. Very slightly restored where damage has occurred. See figure 2 for instructions on how to use this figure to estimate horizontal and vertical disparities $\Delta P_x$ and $\Delta P_y$ between repetitions. See tables 1 and 2 for estimates of these disparities. See Luce (1960) or Meehan (1996) for photographic reproductions of the originals (bottom panel is black and white in print but color online, see http://dx.doi.org/10.1068/p6311).

word, and eventually book production became established into the originally pagan, predominantly aliterate, oral culture of the northern British Isles, Insular interlace was drawn and painted on parchment, where the most finely detailed examples occur (for instance, Nordenfalk 1995, pages 27–43).

### 2.2 *Microscopically detailed wallpaper illusions: Evidence of stereocomparison?*

A second and more telling clue to the micrography problem is that the most intricate designs commonly occur in patterns that repeat so exactly that the repetitions can be free-fused to form wafer-thin, microscopically detailed, stereoscopic images which, by and large, easily qualify as wallpaper illusions (figure 1). For corresponding points in a pattern to be fused into a coherent stereoscopic image, the disparity $\Delta P$ between each pair must fall consistently within Panum's fusional area, typically ~10 min of arc (~0.003 radians) for points near the center of the visual field (see, for instance,

Howard and Rogers 1995, pages 315–317; Hershenson 1999, pages 37–40, 56). For a horizontal disparity $\Delta P$, this means that arctan $(|\Delta P|/D) < 0.0015$ radians, or for practical purposes $|\Delta P|/D < 0.0015$ [since arctan $(x) \approx x$ for $x \ll 1$; see figure 3]. At a normal reading distance $D = 300$ mm, this means that the maximum fusible disparity $\Delta P_{\max} > 0$ is of magnitude $\Delta P_{\max} \approx 450$ µm $\approx 0.5$ mm for a wallpaper illusion. For a stereopair intended to give a strongly three-dimensional image, on the other hand, and particularly with a stereopair involving lines, not points, stereoscopic images can indeed be formed in which the offset $|\Delta P| > \Delta P_{\max}$ with respect to any given fixation point. In the extreme, as in Wheatstone's original stereopairs (for instance, Wheatstone 1838, plate XI), the viewer must 'focus' up and down by changing the vergence of the eyes, and hence the fixation point, to take in the entire image (see figure 3).

A $\pm 0.5$ mm level of precision (that is, $|\Delta P| < 0.5$ mm) is relatively easy to achieve consistently at normal reading distances in curves drawn with compass and straight edge, but not with more complex curves that would be drawn on a macroscopic scale with a French curve, much less in similar curves drawn freehand on a microscopic scale in lines spaced a fraction of a millimeter apart (see table 1, figure 1). The tolerances in the finest examples of Insular illumination range down to about $\pm 0.2$ mm across large areas of a page (tables 1 and 2; not counting comparably small, systematic deviations spread across an entire page, which are accountable to slight differential shrinkage of the parchment). A $\pm 0.2$ mm level of precision at a normal working distance $D \approx 300$ mm corresponds to an angular error of less than $\pm 0.001$ radians, which approximates the smallest angular error attained in cutting-edge astronomical instruments until the sixteenth century (Price 1957, page 583). Thus it is not easy to explain how the finest Insular illumination could have been rendered largely freehand at this level of precision all across a manuscript page, much less how the precision could have been sustained through the additional steps of adding and touching up each successive color of paint (four in figure 1; more in later, more intricate illumination)—or indeed how Bruce-Mitford's "delicate and highly efficient tools" could have been anything other than the artists' own eyes.

**Table 1.** (opposite). Ranges $E(n)$ in disparity $\Delta P(n)$ between neighboring, similarly colored repetitions of a design, executed largely freehand, in particularly well-preserved patterns in the finest Insular manuscripts, with $\Delta P(n)$ estimated from the apparent relief $\Delta h(n)$ of stereoscopic images according to equation (2) (see figure 3). In each case, the pattern and the matching number $n$ at which the estimates were made can be ascertained from the indicated design spacing $P(n)$ in reproductions of the manuscript page. The measurements and location(s) cited on the page should make clear what features have been compared. Notation: 1-D = one-dimensional (frieze) pattern, 2-D = two-dimensional (wallpaper) pattern, L = left, R = right, T = top, B = bottom, $P =$ the spacing between the repetitions compared [$P_x$ = spacing along a frieze pattern, $P_y$ = spacing along the other ($y$) direction in a wallpaper pattern], $F(n)$ = fraction of a stereopair's area fusible, and $E$ = range in disparity $\Delta P$ within the fusible area as estimated from the apparent thickness $t(n)$ according to equation (2) ($E_x$ and $E_y$ as for $P_x$ and $P_y$ above; see figure 3). The approximate maximum number of lines per cm, $C$, is an index of the illumination's complexity.

Estimates are based on photographic reproductions in Meehan (1996) for the *Book of Durrow*; Nordenfalk (1977) for the *Echternach Gospels*, *Lichfield Gospels*, and *Trier Gospels*; Backhouse (1981) and Brown (2002) for the *Lindisfarne Gospels*; and Henry (1974) and Fox (1990) for the *Book of Kells*.

As described in section 4.1, cases marked with an asterisk are hard to explain without both stereocopying from a model and stereocomparison of repetitions by virtue of complexity $C \geqslant 10$ lines cm$^{-1}$, error level $|E| \leqslant 0.5$ mm, and fusibility $F \geqslant 90\%$ of the area. Also marked with an asterisk are unrepeated designs similarly hard to explain by virtue of $C > 10$ lines cm$^{-1}$ both horizontally and vertically. Marks with two asterisks are cases likewise hard to explain, but in both $x$ and $y$ directions, suggesting oblique comparison, as in figure 2. Marked with a dagger are cases of illumination intricate enough to be hard to explain without stereocopying alone. Marked with a double-dagger are cases thought likely to have been neither stereocopied from a template nor stereocompared with one another. In some cases, particularly telling features are marked as well.

| Manuscript (date/years AD) | Page | Feature, location | Area/ mm × mm | $C_{max}$/ lines $cm^{-1}$ | $P_x(, P_y)$ /mm | $F_x(, F_y)$ /% | $E_x(, E_y)$ /mm |
|---|---|---|---|---|---|---|---|
| *Book of Durrow* (~670–680) | *84v | 1-D interlace, L&R borders | 128 × 19 each | ~10 | 32 | ~95 | 0.2 |
| | **85v | 2-D interlace, page center | 115 × 180 | ~10 | 35, 35 | 95+, 95+ | 0.2, 0.2 |
| | *124v | 1-D interlace, L&R borders | 122 × 19 each | ~10 | 47 | 95+ | 0.2 |
| | **125v | 2-D interlace, page center | 54 × 114 | ~10 | 28, 28 | 90–95, 90–95 | 0.5, 0.5 |
| | **191v | 1-D interlace, T&B borders | 64 × 21 each | 10–15 | 21 | 90–95 | 0.4 |
| | *192v | 1-D interlace, paired panels, T&B | 111 × 60 each | 5–10 | 27 | 90–95 | 0.5 |
| *Echternach Gospels* (~690) | *18v | 1-D interlace, paired border segments, L&R | 95 × 9 each, for each | 10–15 | 27 | 95+ | 0.2 |
| | *177r | 1-D interlace, initial "I" | 95 × 5 | ~15 | 10 | 95+ | 0.1 |
| *Lindisfarne Gospels* (~700–720) | *2v | 1-D interlace, L&R borders | 213 × 10 each | ~15 | 91 | 95+ | 0.4 |
| | *26v | Interlace T panels, L&R | 60 × 60 each | ~15 | 114 | 95+ | 0.3 |
| | | Interlace B panels, L&R | 60 × 126 | 15–20 | 114 | 95+ | 0.3 |
| | | Paired interlace B panels, L&R | 30 × 65 each panel | 15–20 | 30 | 95+ | 0.2 |
| | *139r | 1-D interlace, R border | 198 × 8 | ~20 | 66 | 95+ | 0.3 |
| | | 1-D interlace, B border | 144 × 10 | ~20 | 37 | 95+ | 0.3 |
| | *211r | 1-D interlace, R border | 198 × 10 | 15–20 | 59 | 95+ | 0.2 |
| *Book of Kells* (~800) | †40v | Two 1-D interlace panels, L border | 135 × 21 each | 10–15 | 30 | 60–70† | 0.3 |
| | †130r | Two 1-D interlace segments, B–L border | 32 × 11 each | ~20 | ~25 | ~75† | 0.2 |
| | †200r | 1-D interlace, B–L border | 116 × 24 | 10–15 | 30 | ~60† | 0.3 |
| | †29r, †33r, †34r, †130r, †188r | Especially complex unpaired designs | Typically 10 × 10 to 20 × 20 | Typically 15–20, highest 30–35 | – | – | – |
| | ‡200v, ‡201v | ‡Calligraphy: 17 regular repetitions of '*fuit*' on each page | 250 × 30 each page | 3–4‡ | 14 | 95+ | 0.2 |
| *Lichfield Gospels* (~730–750) | ‡220 | Interlace, T panels, L&R | 63 × 63 each | 15–20 | 110 | ~75‡ | 1.1‡ |
| | | Interlace T panels, L&R design triplets | 21 × 63 each, for each | ~15 | 21 | 80–85‡ | 0.5 |
| *Trier Gospels* (700–750) | ‡5v | 1-D interlace, B panel | 13 × 109 | ~10 | 42 | ~70‡ | 0.6 |

**Table 2.** Stereocomparison among roundels on the top and bottom panels of folio 191v in the *Book of Durrow* (figure 1). Abbreviations: $F(n)$ is the fraction of stereopair's area which can be fused; $E_x(n)$ is the range in horizontal disparities $\Delta P_x(n)$ and $E_y(n)$ in vertical disparities $\Delta P_y(n)$ among repetitions as estimated from the apparent thicknesses $t(n)$ of the stereoscopic images according to equation (2), and $n$ is the matching level (see figure 3). Disparity range $E(n)$ refers only to the fusible areas. The $x-y$ coordinate system is explained in figure 2; the notation, in figure 3. Repetitions are counted from 1 to 5 from left to right in figure 1. Estimates of disparity ranges $E_x(n)$ and $E_y(n)$ along each panel are limited to the central three repetitions (2–4) on a panel because the repetitions at either end (1, 5) are not fully symmetrical with them. Though disparities at levels $n = 2$ appear slightly larger on average than those at level $n = 1$, the differences within and between groups by direction $(x, y)$ as well as by matching number are not statistically significant by $F$-test.

| Panel(s) | Repetitions compared | Measurement | $F(n)/\%$ | $E(n)/\text{mm}$ |
|---|---|---|---|---|
| Top | 2–4 | $\Delta P_x(1)$ | 95+ | ±0.4 |
| Bottom | 2–4 | $\Delta P_x(1)$ | 95 | ±0.4 |
| Top | 2–4 | $\Delta P_y(1)$ | 90 | ±0.4 |
| Bottom | 2–4 | $\Delta P_y(1)$ | 90+ | ±0.6 |
| Top | 2, 4 | $\Delta P_x(2)$ | 95 | ±0.7 |
| Bottom | 2, 4 | $\Delta P_x(2)$ | 95 | ±0.6 |
| Top | 2, 4 | $\Delta P_y(2)$ | 90+ | ±0.7 |
| Bottom | 2, 4 | $\Delta P_y(2)$ | 90+ | ±0.5 |
| Top versus Bottom | 1–5 | $\Delta P_x(1)$ | 90 | ±0.6 |
| Top versus Bottom | 1–5 | $\Delta P_y(1)$ | 90+ | ±0.6 |

Van Stone (1994, page 241), an accomplished artist, suggested that the most detailed work was done by sharp-eyed myopes like himself. Bruce Rabe (personal communication, 1998), an accomplished draftsman so nearsighted as to be legally blind, confirmed the possibility, and also pointed out that stereocomparison could be used to particular advantage in copying by someone like himself who can work at distances of only a centimeter or two. Certainly a small working distance provides high magnification without artificial lenses, but does not in itself explain the fusibility of microscopically detailed designs spaced more than a few millimeters to either side of the particular nearsighted artist's interpupillary distance. As table 1 shows, designs commonly repeat on harmonics of about 60 mm, as consistent with stereocomparison, but over a range wide enough to suggest that working distances were not necessarily very small.

There remains the question whether the stereoscopic fusibility is a cause or an effect. With most examples of Insular illumination it likely is an effect. Here we are concerned almost entirely with the finest examples, those detailed enough to defy easy explanation in terms of contemporary technology.

### 2.3 *Technical background: Detecting and gauging microscopic irregularities*

A viewer can estimate copying disparities $\Delta P(n)$ between corresponding points in stereoscopically paired repetitions of a design from the apparent height $\Delta h(n)$ of that point in the stereoscopic image (figure 3). As can be found from similar triangles in figure 3,

$$\Delta h(n) \approx \left(\frac{D}{B - nL}\right) \Delta P(n)\,, \tag{1}$$

where $n = 0, \pm 1, \pm 2, ...$ is the matching number ($n > 0$ for divergent matching, $n < 0$ for convergent matching, $n = 0$ for normal matching), $D > 0$ is the viewing distance, $B > 0$ is the viewer's interpupillary distance, $L > 0$ is the design spacing, and $\Delta P(n)$ is the disparity between corresponding points at matching number $n$ (for derivation of this, the 'parallax formula' of aerial surveying, see, for instance, Ritchie et al 1988, pages 100–101). Here $\Delta h(n)$ is the apparent depth of the image as it appears on the scale of the stereogram

itself, not the physical depth $\Delta H(n)$ of the image as it could be measured with a photogrammetric stereoplotter (see, for instance, Ritchie et al 1988, pages 103–105).

Depending on how the design's spacing $L$ is attuned to the viewer's interpupillary distance $B$, disparities can be estimated quite exactly from the relief of the stereoscopic image. Notice that the factor $\Delta h(n)/\Delta P(n) \approx D/(B - nL)$, represents magnifying power, and that the viewer can vary this power by changing the vergence of the eyes so as to change the matching number $n$ (figure 3). Notice also that the artist, in addition, can increase the magnification dramatically by choosing the design spacing $L$ to harmonize with his or her own individual interpupillary distance $B$ so that $(B - nL)$ can be made very small at a certain degree of divergence of the eyes ($n > 0$) [but ideally no less than a few millimeters, beyond which the approximation in equation (1) breaks down, and little more is to be gained]. For instance, at the viewing distance $D = 300$ mm with $B - nL = 10$ mm, copying disparities $\Delta P(n)$ can be magnified about as powerfully as the stereopair itself could be magnified under a dissecting microscope: $\Delta h(n)/\Delta P(n) \approx 300/10 = 30\times$.

The maximum fusible disparity $\Delta P_{\max} \approx 0.0015D$ corresponds by way of equation (1) to a maximum apparent relief $\Delta h_{\max} > 0$ for the image formed while the eyes are on any one fixation point, that is, while the viewer is not 'focusing' up and down by changing the vergence of the eyes to raise or lower the fixation point.

Generalizing equation (1) to apply to points all across a stereopair, the range $E(n) > 0$ in the maximum range in disparities $\Delta P(n)$ about the mean offset $P(n)$ is found from apparent thickness $t(n) > 0$ of the stereoscopic image:

$$E(n) \approx \left|\frac{B - nL}{D}\right| \left[\frac{t(n)}{2}\right], \tag{2}$$

where $t(n)$ is the difference between the maximum apparent depth $\Delta h(n) < 0$ and the maximum apparent height $\Delta h(n) > 0$ of the image. The particular advantage of stereocomparison over point-to-point measurements of disparity $\Delta P(n)$, such as made with a parallax bar, is quick and convenient estimation of the spatial distribution as well as the magnitude of disparities all across the stereopair, not just between individual points taken to correspond.

The maximum range in fusible disparity $E_{\max}$ in stereocopied work should approximate $\Delta P_{\max} \approx 0.0015D$, though wandering of the artist's fixation point up and down during stereocopying, or subsequent differential shrinkage of the parchment, could increase observed $E$-values by small amounts.

Just as it is possible that $|\Delta P| > \Delta P_{\max}$ in stereograms like Wheatstone's originals, so it is possible that $t_{\max} > 2h_{\max}$. So long as $t_{\max}$ as estimated by changing the vergence of the eyes is not very much larger than $2h_{\max}$, equation (2) should be adequate for estimating the artist's level of error, $E$.

## 3 The 'stereomicrography hypothesis': Micrography by stereoscopic means

The proposed solution to the 'micrography problem' is that the finest Insular illuminators used their presumably unaided eyes in the following ways: first, as a camera lucida to fill a measured lattice grid with working copies of the design; second, as a stereocomparator to detect disparities among the copies from the relief of stereoscopic images, as some editors do in proofreading and as some cashiers do in checking for counterfeit currency (for instance, Brewster 1856, pages 90–106; Luckiesh 1922, pages 37–43; Howard and Rogers 1995, page 30); and finally as a stereomicrometer to minimize these disparities as the illuminator worked by successive approximation to make the repetitions as nearly indistinguishable as possible by making the stereoscopic images as flat as possible. Accuracy could have been improved by taking advantage of the symmetry of the lattices and the designs themselves, as suggested in figure 2.

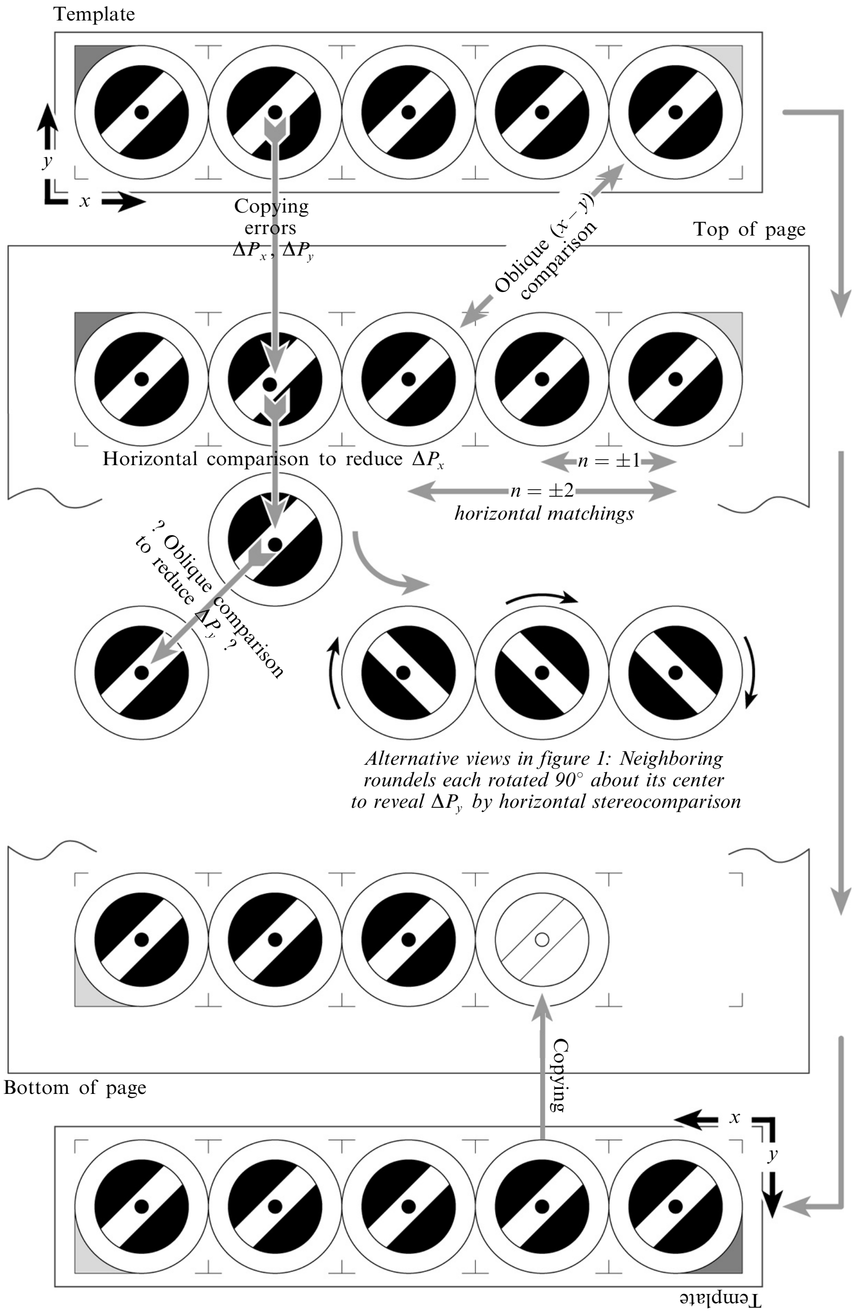


**Figure 2.** Schematic view of the top and bottom of folio 191v in the *Book of Durrow* (figure 1), suggesting how the artists used the eyes first as a camera lucida to transfer the frieze from the template onto the top and bottom of the page, and then as a stereocomparator and stereomicrometer to detect and correct horizontal copying disparities and, perhaps, vertical disparities from the original stereocopying as well. Asymmetries in the roundels between the top and bottom panels in figure 1 show that the template was indeed rotated 180° between copying the one and copying the other, as suggested here. The diagram also explains how individual roundels have been rotated 90° in figure 1 so that uncorrected vertical errors will stand out in stereoscopic relief, and can be compared in magnitude with horizontal errors by comparing the relief of stereoscopic images.

The hypothesized technique is not without precedent: it is in essence the widely used Howard – Dolman test of stereoacuity done in reverse, with viewers discriminating microscopic linear distances by exercising their ability to distinguish tiny angular differences, rather than the other-way round (see Howard 1919; Howard and Rogers 1995, page 151; figure 3).

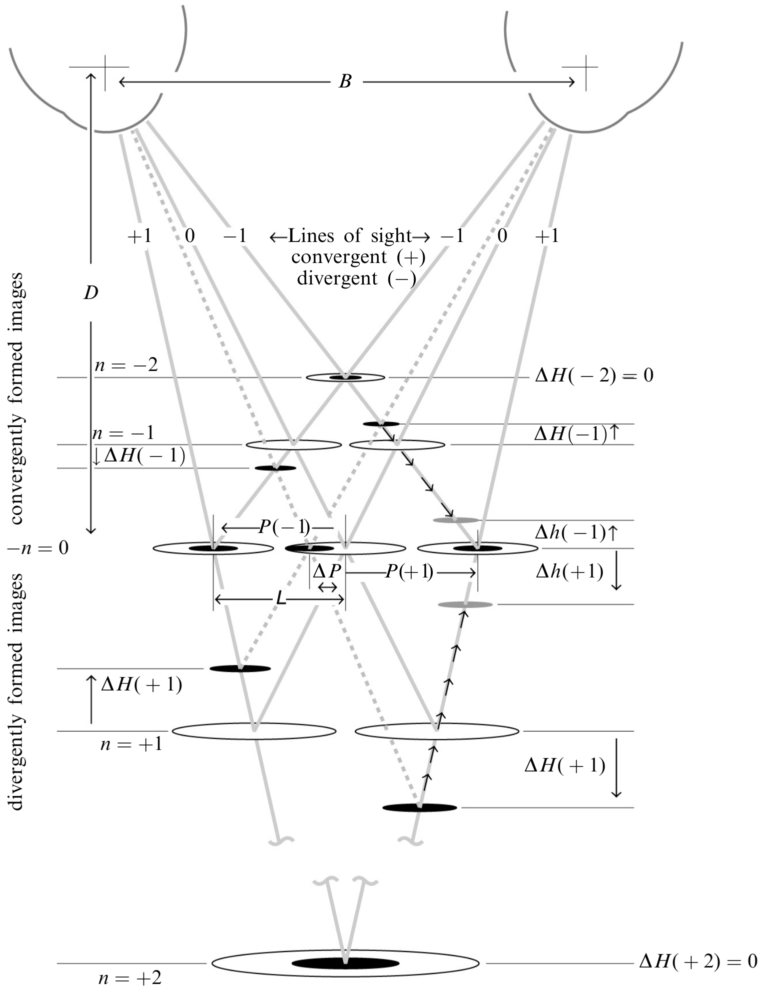


**Figure 3.** Two overlapping Keplerian constructions to illustrate how early medieval artists could have magnified copying errors $\Delta P$ in a repeating pattern powerfully enough to create microscopically detailed designs as parts of that pattern, thereby enabling the artists to work in microscopic detail centuries before the earliest known suitably high-quality artificial lenses. The parchment page is at level $n = 0$. The three open ellipses represent repetitions of a pattern, as in figures 1 and 2; and the closed ellipses represent corresponding points on the repetitions. Stereoscopic images are formed at levels $n = +1$ and $n = +2$ by diverging the eyes, and at levels $n = -1$ and $n = -2$ by converging them. $\Delta H(n)$ is the measurable relief of the image at level $n$ as it could be measured on a stereoplotter with air photos, and $\Delta h(n)$ is the apparent relief of that image as it appears to the viewer on the scale of the stereogram itself. By choosing the design spacing $L$ so as to harmonize with his or her interpupillary distance $B$, an artist can magnify copying errors $\Delta P(n)$ as powerfully in the apparent relief $\Delta h(n)$ of a stereoscopic image as the stereogram itself could be magnified under a dissecting microscope.

3.1 *The hypothesized illumination process*

As envisioned, the illumination process involved two sets of procedures, called for convenience stereocopying from a template, and stereocorrection of copies against one another, as figure 2 suggests for the panel in figure 1.

3.1.1 *Stereocopying.* This is copying the design or pattern off the template using the eyes as a camera lucida. The template is aligned alongside the page, as in figure 2, to fix it in position, and to lay down measured guidelines for the copy. Then the pattern is copied onto the target grid, minimizing the error $\Delta P$ by minimizing the apparent relief $\Delta h$ of the stereoscopic image by successive approximation (see figure 3).

There is indeed evidence that illuminators used templates. Nordenfalk (1974) noted that pattern pages were referred to by Cassiodorus (~490 – 585 AD, one of the founders of the Western monastic tradition in manuscript production), and identified a surviving example, an early medieval page depicting five varieties of interlace reminiscent of the Insular variety. Surviving guidelines and pinpricks on the *Lindisfarne Gospels* and other illuminated Insular manuscripts suggest that physically separate templates could indeed have been used to repeat designs on many carpet pages (Bruce-Mitford 1960; Brown 2003, pages 213 – 226). Otherwise, similar templates for finely detailed ornamental panels evidently were used in Insular ornamental metalwork, for pattern pieces inscribed on bone, in particular, have been common archaeological finds (for instance, Craddock 1989).

Precise correspondences between small irregularities in the two frieze panels in figure 1 are clear evidence that both were indeed copied from one and the same template, and that the template itself was rotated 180° with respect to the page between the copying of one panel and the next, as shown in figure 2. Corresponding irregularities in the central three roundels along each panel are apparent without stereocomparison, especially in the outlines of the outermost whorls. Figure 1 is set up to facilitate verification by stereocomparison.

3.1.2 *Stereocorrection.* This is refinement of a stereocopied design or pattern based on stereocomparison among copies. For the frieze in figure 2, the artist would have rotated the page with its attached template 90° (or some other angle, depending on the pattern's symmetry), and then systematically stereocompared repetitions all along the pattern, minimizing copying errors $|\Delta P|$ along as many different directions as possible by minimizing the apparent thickness $t$ of the stereoscopic images (for instance, $|\Delta P_x|$ and $|\Delta P_y|$ in figure 2, as minimized by minimizing the apparent thickness of images, $\Delta t_x$ and $\Delta t_y$ along the respective directions).

For best results, the illuminator would have stereocompared each copy of a design back and forth with the template as well as with neighboring copies, iterating the procedure to the point of diminishing returns.

A similar procedure would have been used for best results with isolated copies of a design, especially a highly symmetrical design such as a Maltese cross or three-armed spiral. The template would have been stereocompared with the copy from several positions all around the compass to minimize both $|\Delta P_x|$ and $|\Delta P_y|$.

There is indeed evidence that scribes and illuminators worked by successive approximation, correcting their work as they went along, for they commonly were pictured with a pen or brush in one hand and (unless they happened to be presumably unerring Evangelists) with an erasing knife in the other, poised to correct mistakes (Alexander 1992, pages 4 – 34).

The same stereocorrective approach could be taken with designs that are not serially repeated, such as isolated interlace knots. The copy would have been refined by securing the template in one position after another with respect to it so as to get the same effect as comparing one repetition of a design in a wallpaper pattern with its neighbors.

Two-dimensional (wallpaper) patterns would have been created in much the same way as the one-dimensional (frieze) pattern in figures 1 and 2 by filling a two-dimensional lattice with repetitions of a design.

Of course, stereocopying of a pattern need not have been followed by stereocomparison of the repetitions. For instance, once a pattern has been stereocopied, the repetitions in the copy need not have been stereocorrected against one another, which helps explain patterns like some noted for the *Lichfield Gospels* and *Book of Kells* in table 1, in which repetitions of an intricate, microscopically detailed pattern cannot be free-fused over a quarter or a third of their area.

3.2 *How could microscopically detailed templates have been created?*

The template for a design could have been created and refined through a process of successive approximation by the two operations described above. A good strategy would have been to create and refine a template in the context of a two-dimensional pattern by the following procedure: first, to lay down a measured grid in the form of a two-dimensional lattice of a spacing and symmetry appropriate to the design; next, to draft the first approximation of the design in a cell near the center of the grid so as to establish the relationship between critical points on the design and lattice points on the grid; then to fill the surrounding cells with working copies of the design while using the eyes as a camera lucida; and finally to stereocompare as many working copies of the design as possible along as many different directions as possible to average out and minimize copying disparities along as many directions as possible so as to take advantage of the design's symmetry in detecting disparities among as many copies as possible, as suggested in figure 2. The repetition or repetitions taken as the template would be chosen from somewhere near the middle of the wallpaper panel, where irregularities can be evened out and minimized by stereocomparison with the greatest number of neighbors, again in the manner of figure 2.

3.3 *Technical challenges and opportunities*

For the hypothesized stereomicrographic technique to work, the copyist must be able to keep copying errors consistently within Panum's fusional area. An artist able to do this can, in principle, use free fusion to reduce the error as much as two orders of magnitude further, right down to the limits of human stereoacuity, $|\Delta P|/D \approx 10^{-5}$ (for instance, Howard and Rogers 1995, page 155). In practice, however, artists' steadiness and eye–hand coordination probably would keep the improvement to more modest levels.

One sees the potential for a stepwise increase in the accuracy of copying, and a corresponding stepwise increase in the intricacy of the designs and patterns that can be created and copied. The stereomicrography hypothesis thus provides an explanation for the seemingly qualitative difference in precision and intricacy that distinguishes the finest Insular illumination from all other early medieval varieties, the difference that Giraldus Cambrensis associated with the presumably qualitative difference between the work of men and of angels.

Another challenge in using the hypothesized technique effectively is that luminance due to contrasts in color can compromise a viewer's ability to estimate stereoscopic relief $\Delta h$ and hence copying error $\Delta P$, or even to determine whether at least some of the luminance is due to disparities $\Delta P$ too large to be fused. The bottom panel in figure 1 gives some idea of the problem. One way of improving the accuracy would have been to make the template as neutral as possible, with shapes drawn in ink or dry point on blank parchment. The top four panels in figure 1 give some idea of the improvement attainable by reducing the contrast.

Certainly the hypothesized technique would not appeal to anyone with any other means of achieving the high magnification needed to work in microscopic detail, and

indeed might never even occur to such a person. The author's experiments in drawing microscopically detailed patterns with the unaided eyes have left him convinced that the technique is workable, but practical only for those with the vision, steadiness, and eye–hand coordination of an adult decades younger.

3.4 *Why would Insular illuminators have taken the trouble?*
It is hard to imagine why anyone would devise or employ the hypothesized stereomicrographic technique without some compelling reason to do so. Insular artists did indeed have such an incentive. In their time, the rival Celtic and Roman churches were waging what amounted to a century-long propaganda war for the northern British Isles, a contest in which lavish artworks figured importantly, as detailed in the Venerable Bede's *History of the English Church and People* (for instance, Henderson 1987, pages 177–228). The geometric ornament adapted from the originally aliterate and pagan Celtic and Anglo-Saxon worlds, newly hybridized as the Insular style, was squared off against the figurative art introduced along with the Bible from the Mediterranean world. In an apparently conciliatory gesture, the two styles are repeatedly represented faced off against one another in the *Lindisfarne Gospels*, with an Evangelist portrait on one side and a carpet page on the other. Illumination like that in the *Book of Kells* no doubt was intended not simply to impress, but to appear genuinely miraculous, as it did to Giraldus Cambrensis centuries later in his testament to the illuminator's lasting success (see O'Meara 1951, page 67).

**4 Evaluating the stereomicrography hypothesis**
No contemporary descriptions of Insular illumination techniques survive, and there is reason to suspect there never were any. The need for secrecy is obvious, especially considering the role of art described in section 3.4 above. What is more, secrecy is in keeping with what is known of medieval Irish artistic taste and practices; for, as Giraldus observed about both manuscripts and music, "the perfection of their art seems to lie in their concealing of it, as if 'it were the better for being hidden. An art revealed brings shape'" (O'Meara 1951, page 87, see also page 67). Evidence must be sought instead in the illumination itself, and necessarily would be circumstantial at best.

Much of the following discussion, that, like that preceding, is hung on the example in figure 1, which, as characteristic of the *Book of Durrow*, represents an early and (comparatively speaking) technically primitive stage in Insular illumination, one in which the detail ordinarily can be resolved adequately at 1 : 1 in ordinary halftone illustrations (figures 1 and 2; table 2). Photographic plates are needed for the finer details in the *Lindisfarne Gospels* and *Book of Kells*.

4.1 *Test criteria*
The principal test of the stereomicrography hypothesis is the extent to which well-preserved repetitions of a microscopically detailed pattern of freehand lines can be free-fused. Here the test criteria are quantified as follows:
(i) The intricacy of a design or a pattern, as measured by $C$, the (approximate) maximum number of lines that a centimeter-long pin could touch if dropped onto the illumination in question. To keep parallel or more-or-less concentric lines separate while drawing them at spacings $C \geqslant 10$ lines $\text{cm}^{-1}$ the artist obviously must keep copying disparities $|\Delta P| \leqslant 0.5$ mm (preferably $\ll 0.5$ mm) for such lines not to touch. The minimum required $|\Delta P|$ approximates the maximum disparity $\Delta P_{\max} \approx 0.5$ mm for corresponding points to be fusible at normal reading distance $D \approx 300$ mm—perhaps not coincidentally. As noted in section 2.2, $|\Delta P| \leqslant 0.5$ mm at $D \approx 300$ mm approaches the maximum angular precision attained in scientific instruments until the Renaissance; hence the reason to consider $C \geqslant 10$ lines $\text{cm}^{-1}$ as indicative of stereomicrographic copying.

(ii) Copying precision, as measured by the maximum fusible copying disparity, $E(n)$, this as estimated stereoscopically by the viewer across the whole field of view [equation (2)]. $E(n) \leqslant 0.5$ mm suggests stereomicrographic copying for the same reasons that $|\Delta P| \leqslant 0.5$ mm and $C(n) \geqslant 10$ lines cm$^{-1}$ do.

Notice that $E_x$ and $E_y$, like $|\Delta P_x|$ and $|\Delta P_y|$, need not be equal, and that differences could indicate whether or not repetitions were stereocorrected against one another, as explained in section 3.1 (figure 2).

(iii) The degree of fusibility of repetition, as measured by $F(n)$, the percentage of the area of a stereopair that is fusible (which is tantamount to the percentage of the area over which $E \leqslant 0.5$ mm). It seems reasonable to expect that a skilled and conscientious illuminator could attain a fusibility $F(n) \geqslant 90\%$ at normal working distance between whatever repetitions were stereocorrected against one another. Repetitions most likely to have stereocompared (accurately, at least) are those no farther apart than the viewer's interpupillary distance $B$, which is to say design spacing $P(n) = |nL| \leqslant B$. Extraneous factors such as staining or deterioration of the parchment, or partial erasure during cleaning (a particular problem with the *Book of Kells*), can lower $F(n)$ more or less independently of $E(n)$.

Notice that $F_x$ and $F_y$, like $E_x$ and $E_y$, need not be equal, and that differences could indicate whether or not repetitions were stereocorrected against one another (figure 2).

It would be quite possible for an artisan to use the proposed stereomicrographic technique to haphazardly copy design of any complexity $C$, and to duplicate it haphazardly ($F_y \ll 90\%$) without stereocomparing copies for consistency. Work with the following combinations of characteristics appear likely to have been created with the proposed stereomicrographic procedures because such workmanship is hard to explain in any other terms:

(a) Stereomicrographic rendering of designs: designs microscopically detailed ($C \geqslant 10$ lines cm$^{-1}$), stereopairable or not.

(b) Stereomicrographic repetition of designs without stereocorrection of copies against one another: designs stereopairable, microscopically detailed ($C \geqslant 10$ lines cm$^{-1}$) and, where copies can be stereocompared along the $y$-direction (as they can for example in figures 1 and 2), or from repetitions of the same design in two dimensions (as in the *Book of Durrow*'s folios 85v and 125v, table 1), $F_x < F_y \geqslant 90\%$, and especially $E_x > E_y \leqslant 0.5$ mm.

(c) Stereomicrographic repetition of designs with stereocorrection of copies against one another: designs stereopairable, microscopically detailed ($C \geqslant 10$ lines cm$^{-1}$) designs, and, where the $y$-direction in figure 2 can be checked as it can in figure 1, or with two-dimensional repetition of the designs (as in the *Book of Durrow*'s folios 85v and 125v), $F_y \approx F_x \geqslant 90\%$, and especially $E_y \approx E_x \leqslant 0.5$ mm.

### 4.2 *Results*

The sample considered here consists of two representative groups of manuscripts. First are the three Insular manuscripts generally acknowledged as the finest of their particular times: the *Book of Durrow* (~670–680 AD), *Lindisfarne Gospels* (~700–720 AD), and *Book of Kells* (~800 AD). Second are three examples representing the next-best class in Insular illumination for their respective times: the *Echternach Gospels* (~690 AD), *Lichfield Gospels* (~730–750 AD, a generation after *Lindisfarne Gospels*: Nordenfalk 1977; Brown 2003), and *Trier Gospels* (~700–750 AD). Ornament in the remaining 75 or so Insular manuscripts appears coarse enough ($C \ll 10$ lines cm$^{-1}$) and simple enough (consisting mainly of segments of straight lines and circles easily drawn with or without compass and straightedge) not to require any special explanation.

By the criteria outlined above, the $C$-, $E$-, and $F$-values cited in table 1 for what appear to be freehand details of the regularly repetitive patterns in the *Book of Durrow*,

*Echternach Gospels*, and *Lindisfarne Gospels* are consistent with the illuminators' use of both stereocopying from templates and stereocomparison of copies among themselves. Similar data on the *Book of Kells* and possibly the *Lichfield Gospels* are consistent with the illuminators' stereocopying from templates, but not with their stereocomparison of the repetitions themselves. Data on the *Trier Gospels* and perhaps the *Lichfield Gospels* suggest that the artists were trying to achieve similar results, but without benefit of stereocomparison.

It would appear from table 1 that the illuminator was content simply to keep errors within the range of stereoscopic fusibility at normal reading distances, and did not try for greater precision or complexity.

4.2.1 *The Book of Durrow.* It would appear from table 1 that the illuminator or illuminators were content simply to keep errors within the range of stereoscopic fusibility at normal reading distances, and did not try for greater precision or complexity.

Of particular note are the indications that the artist compared designs along both the $x$- and $y$-directions in the form of similar degrees of precision ($E$) and fusibility ($F$) along both, and perhaps along oblique $x-y$ directions as well, first in figure 191v (figures 1 and 2; table 2), and second, in two-dimensionally repeated designs on folios 85v and 125v (table 1).

4.2.2 *The Lindisfarne Gospels.* The designs are consistently the most exactly repeated in all of Insular illumination, and evidently are the work of a single artist, who is identified in a tenth-century colophon as Eadfrith, Bishop of Lindisfarne (698 – 721 AD) (Brown and Bruce-Mitford 1960a; Brown 2003, page 109).

4.2.3 *The Book of Kells.* For all the intricacy of some of its illumination, the *Book of Kells* has few instances in which a design is straightforwardly repeated as a stereopair, much less as a pattern. Where patterns occur, they tend to be detailed enough and to repeat regularly enough to suggest stereocopying from a template, but not stereocomparison of repetitions against one another (table 1).

However, there are many instances in which a design or parts of designs are repeated quite exactly, except that the repetitions are rotated with respect to one another, commonly by 60° or 120°, or are mirror images of one another. Some of these are examples of the most intricate designs on the most elaborately ornamented carpet pages in all of Insular art, specifically folios 29r, 33r, 34r, and 130r.

A possible explanation for instances of rotation is that all or part of a design was traced in camera-lucida fashion from a separate template that was pinned first at one position and then at another as the page was being drafted, as suggested above for the *Book of Durrow* and *Lindisfarne Gospels*. One explanation for the instances of mirror symmetry is that the template itself was two-sided and on particularly thin, translucent parchment.

The apparent reason for the considerable range in the quality of the artwork is that *Book of Kells* was illuminated by several different artists over a period of years, one, the creator of the finest work, being known as the 'Goldsmith' (Henry 1974, page 212), and another, more of a rubricator, known facetiously as 'The Master of the Felt Marker' (Van Stone 1994, page 239).

The remarkably consistent calligraphy, apparent throughout the text, is an important hint about how artists were able to reproduce delicate features of the illumination so exactly, involving well-practiced repetition of the pen strokes, whether in forming letters or in crafting abstract designs. Comparably exact repetition was attained in both cases, as can be verified by stereocomparison of the 17 repetitions of the word "fuit" on each of folios 200v and 201v (table 1). Quite conceivably, stereocomparison was used in training scribes as well as illuminators in St Columba's family of monasteries,

as would be consistent with accounts of this famous scribe's reputed miracles of rapid proofreading (see section 5.1).

4.2.4 *Other attempts at microscopic precision?* To judge from the abundance of intricate but stereoscopically unfusible Insular-style interlace in less exemplary Insular manuscripts (and also in subsequent ninth-century Anglo-Saxon and Franco-Saxon manuscripts), many artists apparently unaware of the stereographic technique aimed for but failed to achieve 'wallpaper' as impressively intricate as the *Lindisfarne Gospels* illuminator's. The one surviving carpet page in the *Lichfield Gospels* (~730–750 AD) is a good case in point because, as many art historians have noted, it apparently was based more or less directly on the *Lindisfarne Gospels'* St Matthew carpet page (Nordenfalk 1977, page 83; Backhouse 1981, page 66; Henderson 1987, page 124; Brown 2003, page 315). On first inspection, the *Lichfield Gospels* interlace appears as impressively complex as that of the *Lindisfarne Gospels*, if somewhat less intricate (table 1). Repetitions, however, often cannot be free-fused in detail for reasons that become obvious in the attempt: corresponding features are distinctly irregular both in size (notably with key features such as the eyes of interlaced animals) and also in shape (for instance, different numbers of turns in corresponding repetitions of a coil).

## 5 Discussion

### 5.1 *Who were the stereomicrographers?*

That the finest examples of stereoscopically fusible interlace all occur in manuscripts associated with monasteries of the family founded by St Columba (~521–597 AD) and his disciples—namely, Durrow, Kells, and Lindisfarne—suggests that the stereo-comparative technique may have come down through the Celtic Church, and quite conceivably from St Columba himself, a prodigiously active scribe who, suspiciously enough, was famed for reported miracles of speedy, letter-perfect proofreading of hand-sized psalters such as modern proofreaders might achieve by free-fusion stereo-comparison (for instance, Adomnàn's *Life of St Columba* [i.23]; see Anderson and Anderson 1991; Sharpe 1995, pages 284, 352–353, 378). Included here are not only the *Books of Durrow*, *Kells*, and *Lindisfarne*, but perhaps also the *Echternach Gospels,* a possible product of the Lindisfarne scriptorium (Alexander 1978, page 42f) (see table 2).

That microscopically detailed, stereographically exact ornamental patterns are restricted almost entirely to the few finest Insular manuscripts suggests that knowledge of stereocomparison may have been something of a trade secret known only to a few. The reasons for secrecy are obvious. Illumination like that in the *Book of Kells* no doubt was intended not simply to impress, like the portraiture of Hockney's (2001) Old Masters, but to appear genuinely miraculous, as it did to Giraldus Cambrensis. And what became of the stereomicrographers' know-how? Most likely it was lost along with much else during ninth-century Vikings' systematic destruction of the British Isles' monastery system.

### 5.2 *How could indications of free-fusion stereocomparison have been overlooked?*

How could stereoscopic phenomena have been overlooked and unreported until now in some of the world's best-known and most intensively studied graphic art? This applies in particular to Sir David Brewster, the inventor of the easy-to-use prism stereoscope behind the Victorian parlor craze, who searched back to Euclid and beyond for potentially patent-breaking precedents to Sir Charles Wheatstone's original, desktop-sized mirror stereoscope (Brewster 1856, page 6).

For several reasons, the stereoscopic effects to be seen in Insular manuscripts are easily overlooked. First, stereographically exact repetition of microscopically detailed designs is common only in the few finest of the 80-odd surviving Insular manuscripts.

Second, Insular illumination tends much more to overwhelm with its complexity than to invite close, systematic inspection. Third, the stereoscopic images themselves are easily overlooked, especially by anyone accustomed to the vivid, often intentionally exaggerated three-dimensionality of modern stereopairs, random-dot autostereograms, and virtual-reality systems. If noticed at all, most images could be dismissed as strictly fortuitous wallpaper illusions by anyone who did not stop to consider how early medieval artists could have produced such exactly repetitive, microscopically detailed 'wallpaper'. Otherwise, suggesting there are stereograms in Dark Age illumination could seem very much on a par with suggesting there really was a Connecticut Yankee at King Arthur's court, complete with Victorian parlor stereoscope.

## 6 Conclusion

Is the stereoscopic fusibility of exactly repeated, microscopically detailed designs in the finest Insular illumination simply a coincidence, an artifact of extraordinarily exact freehand copying by highly skilled calligraphers? If so, it is a most remarkable coincidence, considering that stereocomparison is the one apparent means by which illuminators working five centuries before the earliest known spectacle-quality lenses could have obtained the magnification needed to detect and correct errors at each step in crafting multicolored, microscopically detailed designs, and could have achieved tolerances unsurpassed in scientific instruments until the Renaissance. To be sure, much remains to be done in testing the stereomicrography hypothesis, specifically in systematically examining a much larger sample of Insular illumination not from photographic reproductions but from the originals themselves to better document the accuracy of the repetition, to look for further evidence of the illumination in such things as pinpricks and guidelines, and overall to better ascertain in which cases the fusibility is more likely a cause than an effect of the exact copying.

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