Fiat lux: climatic considerations in medieval stained glass aesthetics

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Abstract

As expressions of regional architecture built to last, sacred Gothic structures often possess several adaptations to their prevailing climate regime. However, the late medieval period in Europe is also marked by a transition to cooler and likely cloudier conditions. It is within the context of this climate change that we consider one of the most important considerations in Gothic churches—interior daylighting—during the transition from the Medieval Warm Period to the Little Ice Age. This thesis seeks to determine whether increasingly cloudy conditions over northern continental Europe may have influenced the use of more white glass in the Fourteenth century. With primary illuminance and luminance data collected in Europe, the results indicate that full-colour programs appear to perform best under sunny conditions, whereas later, white-dominated programs provide similar illumination under cloudy conditions. However, this high-translucency glazing is associated with limited lighting gains and major aesthetic drawbacks under sunny conditions.

Résumé

Etant donné que les cathédrales gothiques ont été construites pour durer, plusieurs adaptations aux climats regionaux y ont été apportées. Cependant, la fin du Moyen Âge fut marquée par un changement climatique vers des conditions plus froides et probablement plus nuageuses en Europe du nord continentale. C'est donc dans ce contexte que nous cherchons à comprendre l'un des éléments les plus importants de l'architecture gothique—éclairage naturel intérieur—durant la transition entre la période chaude médiévale et le petit âge glaciaire. En particulier, cette thèse voudrait évaluer la relation entre l'utilisation de plus en plus fréquente du vitrail blanc durant le XIV^{ème} siècle d'un côté et le changement climatique d'un autre côté. Avec des données d'éclairement lumineux et de luminance lumineuse collectées dans plusieurs cathédrales en Europe, les résultats indiquent que les vitraux plein-colorés éclairent mieux l'interieur durant les journées ensoleillées. D'autre part, les vitraux incolorés du XIV^{ème} siècle fournissent un éclairage similaire durant les journées nuageuses, toutefois ils ne présentent que peu d'avantages dans des conditions plus ensoleillées, de plus l'utilisation du vitrail plus transparent produit des effets négatifs sur le plan esthétique.

Table of Contents

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1 Introduction

Shelters have always been integral elements of human society; people have relied on them since prehistoric times to provide vital protection from the outside world. Of all the physical external realities with which humans are concerned, weather and climate are perhaps the most fundamental considerations that go into the construction of shelters. We, as culturally adaptive creatures, have the remarkable ability to build shelters that enable us to live on virtually any region of the earth where food and water are obtainable. People familiar with a given region are often able to devise creative and effective adaptations to their native climates, and these are often seen through the lens of architecture. An often-cited example are the Mediterranean villas of Italy, from the Roman epoch to the Early Modern era, which are suited for dry, sunny climates. For instance, the location and size of villa windows are often strictly controlled to prevent excessive internal heating during the hot summers, and they are frequently designed around fountain courtyards, which provide a cool microclimate dominated by evaporative cooling and act as a relief from intense summer heat. Modern architecture, with its more durable, weather-resistant plastic, metal, and glass materials (and accompanied by the conveniences of modern electrical and heating and cooling systems), has become more global and has diverged from the vernacular prototypes of the past. However, even today local climatic concerns, such as balancing thermal and psychological comfort with daylight energy savings for a given location, are a high priority in the design of any building. Therefore, the small, gradual regional climate transitions associated with global warming can pose significant challenges to modern architects, as discussed extensively in Roaf (2005).

The overarching goal of our research is to examine the vernacular architectural styles of the pre-modern era in order to illustrate the interactive relationship between architecture, as functional shelter design, and the prevailing regional climate. In addition, we hope to demonstrate the modifications these vernacular architectural styles undergo in the face of natural climate change, both as a testament to potential past architectural concerns and the potential wide impacts to architectural design that today's more anthropogenically-driven climate change may have. To limit the scope of such a broad undertaking in which there remains many avenues to explore, in this thesis we selected one variable (lighting), two regions (Northwestern Europe and Mediterranean Europe), one period (the High Middle Ages through the Renaissance), and one architectural style (sacred Gothic—see Appendix I for a glossary of architectural/stained glass jargon) to test this hypothesis of how climate change may affect architectural style.

Furthermore, the medieval period was chosen because of a significant climate transition that occurred between the heart of the Middle Ages, traditionally associated with the Medieval Climatic Optimum or Medieval Warm Period (henceforth abbreviated MWP) in northwestern Europe, and the Little Ice Age (LIA) which officially began during the Late Middle Ages and the Renaissance and continued to the beginning of the pre-industrial era. A more detailed, regional analysis of proxy data and other studies on medieval climate is provided below in Chapter 2. Post-industrial examples of sacred architecture were ignored due to increasingly more efficient forms of artificial interior lighting and eventually electric lighting that accompanied the transition from the Little Ice Age to the industrial era. In addition, early and pre-medieval architectural changes and climate transitions were not considered as part of this particular thesis due to a relative lack of adequately-surviving examples compared to the rich and numerous architectural fragments retained from the later Middle Ages. For example, beyond archaeological investigations and floor plans, few examples of pre-Romanesque architecture remain in Northern Europe, and therefore international Romanesque and Gothic architecture, of which numerous examples exist throughout Europe, were considered the best subjects for analysis.

The effects of climate and climate change on architectural design and aesthetics can perhaps be best described by focusing on various buildings which hold the same function. In this case we chose sacred architecture, focusing on basilicas, cathedrals, abbeys, and large city churches, as the sole focus of this thesis, as these architectural wonders perhaps represent the best-preserved and most innovative examples of buildings from their time. Smaller country parish churches were consequently largely ignored due to significant economical constraints that limited design strategies and technical sophistication. Even with this focus, there are hundreds of potential examples to choose from; often a few medieval churches and cathedrals have been maintained through the ages even in towns, cities, and regions where few or no examples of secular late medieval architecture survive (often destroyed in war or replaced by newer buildings in later eras). As expressions of local pride and piety, medieval cathedrals were the spiritual and cultural focal points of medieval society and were often embellished with carefully-crafted ornamentation, stained glass, sculpture, and painting. Architecturally they were designed on the inside and outside with features that would sustain the building against the elements for centuries. Thus, while following international styles and trends, such as Romanesque and Gothic, sacred buildings from the Middle Ages often possess local adaptations and characteristics that differ from other regions

and allow them to be classified as a form of vernacular architecture (for example, see Pastan, 1994). In this thesis, we distinguish between two separate regions where vernacular architectural expression differ greatly within the same international style—northwestern Europe and the Mediterranean. Even within northwestern Europe we must further make distinctions between English, French, and German churches.

1.1 Sacred Architecture as an Indicator of Climatic Change

The possibly significant relationship between climate regimes and medieval sacred architecture in Europe is not a new concept. It has been treated by several authors in the past, most extensively by William Wachs in his 1964 dissertation/book *The Historical Geography of Medieval Sacred Architecture*. As in our study, Wachs demonstrates a variety of parameters that differ between southern (Mediterranean) and northern examples of church architecture and attributes these to different climate adaptations between the two regions. For example, Wachs provided a detailed analysis of roof pitch and tile in both northern and southern cathedrals, with lower roof inclinations and semi-cylindrical tiles being preferred in the drier Mediterranean climate and slate tiles with high roof inclinations (better snow shedding and less likely to be pierced by persistent rainfall or frost) favoured in Northern Europe during the Gothic Age (Wachs, 1964). In addition, the rapid evolution of guttering systems in northwestern European Gothic architecture, along with the inconsistent use of guttering in the Mediterranean basin and exposure of exterior sculptures and paintings to the elements in many Mediterranean structures, suggest similar regional climatic adaptations to the predominate rainfall regime.

However, northern Romanesque churches often possessed lower roof inclinations, a less consistent use of guttering systems, and a greater exposure of sculpture (and sometimes painting) to the elements, sometimes well after architects had already developed the technology to change these factors (Wachs, 1964; Matthews, 2002). To rationalize the inconsistencies between the Romanesque and Gothic era in northern Europe, Wachs applies linear progression theory to architectural history, suggesting that northern Europeans were advancing in their architectural prowess and becoming bolder in their separation from Mediterranean influences to produce climatically-suitable vernacular architecture. While innovation, further technological development, and style-changes account undoubtedly for part of the discrepancies between northern architecture in the Romanesque and Gothic periods, it fails to adequately address the fact that Europeans had already developed the guttering systems, flat tiles with sharp roof inclinations, and recessed portals

during Romanesque times yet in many cases chose not to use them. However, Wachs also uses early and mid-twentieth century climatic norms as a suitable means for assessing the motivations of architects living 500 to 1000 years ago. This may work well in some cases but fails to take into account the notable cooling of the climate in northern Europe that had begun before 1500.

In view of the above, the explosion of protective measures from the rain and frost during the Gothic era may not be due to a sudden awakening to technology on the part of Northern Europeans but rather an adaptive measure taken upon observing the increasingly apparent deleterious effects of rain and frost on their preexisting architecture and art (as was certainly observed in the collapse of the tower and nave of Troyes Cathedral over the course of its construction during the fourteenth century) (Murray, 1987). In other words, part of the discrepancy between the architectural practices of the Romanesque and Gothic periods in Europe north of the Alps may be related to a slow, gradual climate shift toward the LIA that required buildings to have more protection from wind and rain. This seems particularly plausible when considering that Mediterranean guttering, portals, and window sizes remained virtually unchanged during the switchover to Gothic at a time when northern cathedrals were rapidly evolving new protective features and many northern Romanesque churches were being partly or entirely replaced in the newer Gothic style.

1.2 Interior Lighting Strategy and Window Sizes from the Romanesque to Gothic Periods

Another variable that seems to have evolved in the north while remaining more or less constant in the south is the interior lighting strategy. In general, lighting, architecture, and climate have always been inextricably linked in the design of church interiors. Light serves to communicate the aesthetics and form of the sacred architectural space, a mode of both expression and utility. Light also serves as the primary illuminator of wall frescoes, mosaics, figural capitals, and other aesthetic devices. Climate, along with latitude, season, and time of day, determines how much daylight is present and where in the sky the most light is available, and as a result it strongly governs how natural lighting is directed into the church. Because in the pre-modern era daylight and candles were the primary sources of interior illumination, medieval churches had to adequately use daylighting with respect to the prevailing climate to attain both aesthetic and functional needs. Given the intricacy with which windows and their spatial coverage and design was treated, it was also clearly of utmost concern to Gothic architects (Janson, 2001).

Wachs also addressed lighting as a climatic variable; he explained that Romanesque and Early Christian churches in the north used window sizes similar to those in Mediterranean churches. Before the invention of more sophisticated forms of buttressing, small window sizes were necessary to support the structural stability of the thick walls. Even so, despite these limitations a general increase in window size can be observed with increasing latitude during the Romanesque period. During the Gothic era external buttressing and other innovations allowed walls in Gothic churches and cathedrals to become thinner and windows to expand across much of the wall space. Upon lifting the limitations in window sizes, light became more readily available for cathedral interiors. Wachs maintained that, given the lower solar angles and cloudier conditions of northern Europe, larger windows were necessary in northern interiors in order to maintain the same illumination as Mediterranean interiors under brighter, sunny skies. Again, Wachs provided a linear progression view of Romanesque architecture as a product of limited innovation; that Romanesque interior lighting is fundamentally inadequate for the north and was unable to provide the necessary lighting required for northern interiors, and that the Gothic style immediately remedied this problem. Mediterranean interiors, on the other hand, can be adequately lit by smaller clerestory windows because of the abundance of strong, direct sunshine in the Mediterranean climate, even in the winter, as demonstrated by a nearly decade-long daylighting climatology developed in Markou et al. (2007). Mediterranean windows are high in the façade to allow the deepest possible interior illumination through internal reflections originating from focused bright spots of direct sunlight; wall mosaics strategically positioned with respect to the windows sometimes serve as both aesthetic elements and diffusers of light. At the very least, the Mediterranean interiors required enough light to illuminate important paintings and frescoes (particularly important in Italy) and/or sculptures (prominent in Late Gothic Spain), and decorations that could not be feasibly or safely illuminated by nearby candles or lanterns.

Thermal arguments also need to be considered when evaluating the daylighting potential of buildings. For example, it has been well documented that, due to the diffuse, darker nature of daylighting in many high-latitude Scandinavian countries, larger windows are more desirable with modern construction materials to maximize illumination (Moore, 1985; Noal, 2003). However, in Scandinavia and other less temperate European climates, window sizes appeared to be severely limited and thicker walls were preferred to avoid the penetration of the winter cold (Wachs, 1964). This did not, however, appear to be of utmost concern in most of England and France, where

window sizes reached exceptional proportions and largely replaced the stonework of the surrounding walls. Similarly, in southern Europe excessive heat during the summer months might have been a concern for some architects and may have excluded the construction of lower-level windows. High windows admitting direct sunlight warm the side walls, and this heat would subsequently rise to the roof, never reaching the laity below). However, with regard to the Mediterranean climate, thermal gains from sunlight filtered through the thick low translucency white glazing and alabaster panels common during the medieval era must have been minimal, and a separate study would be needed to determine how much heat could enter large low-transmissivity windows through conduction from the outside as opposed to conduction through stone. In general, relatively large clerestories and aisle level windows were possible in Spain (León, Sevilla) to the extent that the thermal effects by windows are largely disregarded for the purposes of this study. Interior lighting is assumed to be of greater concern and importance, sometimes to the detriment of thermal comfort in certain seasons (as is clearly the case in the north where unheated winter cathedrals can sometimes be much colder than outside temperatures).

However, there are some important distinctions one needs to make with regard to window designs between northern European and Mediterranean churches. First, surviving examples of Romanesque cathedrals in northern Europe demonstrate the substantial versatility of window sizes, particularly by the late Romanesque period. For example, Norman Romanesque architecture (such as in the Abbaye aux Dames in Caen and Durham Cathedral) indicate that multiple stories of windows were possible during the Romanesque period and that aperture sizes could compete with some Early Gothic styles. In Mediterranean Romanesque interiors, clerestory windows were often limited in size and provided the source for most interior lighting. Low-level windows were relatively rare (for examples see San Vincente in Avila and San Miniato al Monte in Florence). Furthermore, Northern Late Romanesque/Transitional styles (such as St-Martin-des-Champs in Paris and Worms Cathedral), which remained popular well into the thirteenth century and even into the early fourteenth century in Rhineland, demonstrates that the larger northern-style Romanesque windows continued to be sufficient for interior lighting in parts of northern Europe and that a mass conversion to the enlarged Gothic window as soon as the technology became available was not necessarily seen everywhere in new construction projects.

1.3 The Relationships between Window Size and Glazing Material in the Interior Illumination of Romanesque and Gothic Structures

When considering the suitability of Romanesque-style windows for a northern environment, one must consider that a gradual transition from smaller, clerestory-dominant Romanesque windows of the Mediterranean basin to the larger, more numerous Romanesque windows of northwestern Europe can be observed with increasing latitude (Moore, 1985). It is not clear how many Romanesque churches were glazed; texts indicate that major construction projects, such as Reims, Le Mans, and Strasbourg, sometimes included glass. However, for many major churches there is little or no textual or physical evidence for glass during the Romanesque period, and the window apertures might have been filled with waxed cloth or parchment or provided in some cases with adjustable shutters (Lillich, Personal Communication, 2008). However, even in these interiors the windows must have been translucent enough to illuminate interior frescoes, capitals, and architectural detailing (beyond the reach of candlelight), which in some cases played a more prominent role in northern churches during the Romanesque era than during the following Gothic period. We also know that when glass was used to decorate windows, it was often clearer than Gothic glass, using an abundance of more luminous whites, yellows, greens, and light blues to increase window translucence (Grodecki, 1983).

The light-admitting capacity of such early glazing programs can, for example, be illustrated by coloured Romanesque programs such as in the nave of Le Mans, where enough lighting would probably have been present to illuminate (at certain times of the day) the intricate figural Romanesque capitals, sculptures, and patterned stonework that decorate the cathedral's nave and side aisles. Similarly, many Northern Romanesque churches possessed frescoes (Winchester, Canterbury, and others) (Demus, 1970) which required illumination through daylight. A greater use of white in Northern European wall frescoes might have facilitated better contrast so that they could be resolved at darker times; however, Italian and even Cluniac frescoes were almost always richly coloured. While glazing options might have been limited, too much interior decoration (requiring some level of illumination to be appreciated) was provided to so many Romanesque interiors, in the form of interior frescoes and sculpture. The smaller size of many Romanesque structures compared to their later Gothic counterparts also ensured that light entering the building was more intensely concentrated over a smaller volume. Thus, with apertures receiving direct solar radiation, important Romanesque constructions with interior art may not have been significantly darker than their thirteenth century counterparts. Furthermore, there would be no purpose for incorporating potentially destabilizing apertures into the facade if they were not

expected to introduce some ambient illumination to the interior, especially if the windows themselves were not decorated with historiated stained glass (and therefore not provided with a secondary role).

Thus, the transition to Gothic, while experiencing an important shift in the aesthetics and colour of window glazing, was not necessarily associated with a dramatic increase in light (Grodecki, 1983). Instead of the bright, higher translucency glass (whites, yellows, and light blues) that often dominated many Romanesque glazed windows, Gothic apertures, starting with their inception at the Basilique St-Denis, were often largely filled with richly coloured glass that provides greater restrictions on interior lighting (Grodecki, 1983). Therefore, the dramatic increases in window size and coverage at the beginning of the Gothic era was often associated with a decrease in glazing transmission, which would have limited rather than amplified the lighting gains associated with the birth of Gothic architecture. Furthermore, Cistercian architecture in the late twelfth and thirteenth centuries mandated the use of ornamental grisaille glass over coloured glass, and in many cases early Gothic Cistercian abbey churches possessed deliberately smaller apertures than their non-cistercian counterparts (Wachs, 1964). This indicates that medieval architects, by playing with both glazing transmission and aperture size, had a sophisticated sense of how much daylight should enter an interior.

As the New Style evolved in France over the course of the thirteenth century, window sizes expanded considerably, turning cathedrals and churches into virtual glass cages. However, in many cases largely full-colour programs (Chartres) or mixed grisaille/full-colour programs (Reims, Auxerre) continued to be prevalent, limiting overall glazing transmission. In some places stained glass projects reached new levels of colour saturation (such as at Sainte Chapelle, Tours, and Le Mans) by the middle of the thirteenth century. Then, in a rather abrupt change in aesthetic, more white glass was used in churches and cathedrals starting in the late thirteenth and fourteenth centuries (Grodecki and Brissac, 1985). Sacred architecture projects finally made a transition to becoming largely white glass cages, such as in the Abbey Church of St-Ouen and Évreux cathedral. New constructions remained dominated by white glass until high-transmissivity enameled and flashed glass afforded a return to full-colour interiors during the Northern Renaissance. The permanent nature of the change to white-dominated interiors after a persistent tradition of darker, colour programs suggests a dissatisfaction with the earlier aesthetic, perhaps associated with a response to cloud cover changes. Even outside of embattled France, new projects

in the Holy Roman Empire (where the colour tradition was strongest in the north) eventually abandoned their largely coloured windows for silver stained, geometric grisailles, and half-white windows in the fourteenth century (Sherrill, 1927).

Further to the north, English cathedrals, with the exception of Canterbury in southern England, never fully endorsed the largely colour-dominated programs of France and appeared to mix a substantial number of grisailles into their early thirteenth century interiors in addition to adopting increasingly large windows (Marks, 1993; Morgan, 1983). In addition, when colours were used in these programs, such as at Lincoln, they were often less saturated and lighter than those in France, which emphasized darker blues and reds (Arnold, 1925). Thus, England maintained a grisaille-dominated Gothic interior lighting aesthetic almost at the inception of the style, whereas France appeared to relinquish it gradually over the course of the second half of the thirteenth century. In the Mediterranean, both the Gothic style and stained glass were slower to be adopted; sometimes low transmissivity alabaster was used in major projects (never applied in the north due to cloudiness-related constraints) (M. Lillich, personal communication, 2008), and when stained glass was used it was often richly coloured (such as at Assisi, León, and Toledo). Windows also continued to be severely restricted despite the new possibilities for window expansion which the Gothic style afforded. In addition, when northern architectural models were directly adopted their relatively oversized apertures were often filled with richly coloured glass (León and Toledo) which continued to limit interior lighting. Thus, the Mediterranean maintained small windows, and when stained glass was adopted it was often coloured, whereas French cathedrals at first sustained a Mediterranean-style aesthetic with larger windows but very dark glass. Then over a century after the development of the Gothic style, French cathedrals switched to an opposing interior lighting strategy allowing the maximum amount of illumination possible (completing the transition as suggested by Wachs). Therefore, two different trends existed in glazing transmission in the French Gothic style, first opposing and then embracing the increased light levels allowed by greater aperture size (Grodecki and Brissac, 1985).

1.4 Stained Glass, Illumination, and Climate

This study hypothesizes that the grisaille revolution, the transition from the predominately full-colour windows to the largely white-dominated (grisaille and quarry) programs in Gothic France at the end of the thirteenth century may have been driven by an increasing dissatisfaction with the quality and quantity of interior lighting available under the full-colour programs. In turn,

the inability of the coloured glass to provide adequate lighting suggests that the climatological prevalence of cloud cover (as Wachs suggests) and its notable dimming effect on full-colour interiors might have become more of a consideration in the interior light design of French cathedrals by the end of the thirteenth century. On the other hand, Mediterranean cathedrals maintained a consistent dark aesthetic, with small windows and/or low transmissivity (coloured) glazing adequate for sunny conditions, and English cathedrals similarly persisted in their tradition of large windows filled predominately with white glass, as is evident in York, Salisbury, and Lincoln, consistent with a cloudy aesthetic. Thus, the transition in France from full-colour to white-dominated interiors, coupled with the destruction of coloured windows and their replacement with whiter grisailles in some places (such as in Chartres ambulatory) around the same time period, suggests that sacred interiors designed for a sunny, more Mediterranean-style lighting aesthetic were being replaced by interiors dominated by whiter glass more suitable for greater lighting in cloudy conditions. As a result, *medieval architects may have been subconsciously documenting not just a change in aesthetic but also a climate transition associated with an increase in cloudiness*, one that may have been a threshold given the given the persistency of white-dominated programs for nearly two centuries until the innovation of enamel glass and greater use of flashed glass, which provided high-transmissivity coloured programs in the fifteenth and sixteenth centuries.

It may also be suggested that some northern Romanesque churches may have also been designed with the goal of maximizing solar lighting, as many churches where wall thickness is a primary consideration place more apertures in the south nave wall to ensure greater winter solar daylighting (Wachs, 1964). Thus, daylighting in a northern Romanesque interior with largely white glazing (or translucent parchment) and smaller windows at two levels may not have been drastically different from a full-colour Gothic interior with more richly coloured glass and larger windows. This also suggests that the expectation of more solar daylight in churches likely predates the inception of the Gothic style, thus implicating that the grisaille revolution was, regardless of architectural style, a single, permanent shift between two different types of interior lighting strategies.

Previous authors on stained glass have already postulated on the suitability of whiter grisaille and quarry glass for cloudier climate regimes and full-colour programs for sunny climates. Taking Wach's arguments further, stained glass historian Charles Sherrill (1927) argued that

> “the most important factor in the study of stained glass is a suitable illumination of the church’s interior. It must not be too greatly obscured in a northern climate, nor must glare be permitted under southerly skies… England is preeminent in her skillful use of early grisaille—glass without figures or pictures. The finest example of this type is justly the famous Five Sisters, whose group of five glorious thirteenth century lights together fill York Minster’s north transept end. English success in this field came about very naturally, for the cloudy skies so frequent that comfortable island demand that light obscuring colour be used more sparingly than in sunnier lands. This demand for ample lighting was handed down all through the fourteenth and fifteenth centuries…The elaborate and extensive use of canopies during her Perpendicular period was but artistic compliance with this need for sufficient light under her cloudy skies, for the canopies introduced many uncoloured panes… Anyone who has observed the strongly coloured windows of Italy and Spain realizes how necessary was that rich colouration in those sunny lands.”

Similarly, Maurice Drake in his *A History of English Glass Painting* suggests that “perhaps on account of our cloudy skies, white glass has always been more in favour in England than on the Continent.” However, similar to Wachs, Charles Sherrill makes generalizations based on the climate of his own time and also claims that the full-colour programs of northern and central France and parts of Germany during the thirteenth century were done with a lack of functional climatic consideration, a mistake corrected for in later work through the introduction of more grisaille glass as well as the removal of coloured panels from Amiens and Chartres. Like Wachs, he does not consider the possibility that full-colour and mixed colour-grisaille lighting may have been viewed as adequate in the twelfth and first half of the thirteenth century in France but increasingly less so by the end of the thirteenth century and beginning of the fourteenth century. This is perhaps due in part to increasing dissatisfaction associated with a climatic shift in France that was not as readily noticed in the more stably cloudy climates to the north or persistently sunny climate to the south.

While the effects of the grisaille revolution on interior lighting has been thoroughly documented by stained glass historians in qualitative terms, few quantitative measurements (see Sowers, 1966) are available in the relevant literature to assess the actual degree to which grisaille programs provided increased lighting over full-colour interiors. Therefore, as part of this study the author went to Europe to collect both illuminance and luminance data in some of France, Germany, and Spain’s Gothic churches and cathedrals with relatively well-preserved medieval stained glass programs. Both sunny and cloudy interior lighting regimes were assessed in cathedral interiors from full-colour thirteenth century, post-grisaille revolution, and Renaissance interiors, and daylight factors were calculated when possible. Unfortunately, in many cases we could not

find a completely intact program that possessed glass exclusively from one era, as destruction, corrosion, and replacement over the centuries has changed the nature of the original interior lighting to varying degrees in all cases. In particular, the presence of clear modern windows in many cathedrals provides a notable brightening in our measurements. At the same time, however, a few interiors, such as the nave and crossing of Chartres, are likely darker than originally intended due to the current corrosive buildup on the clerestory windows. Thus, our measurements provide not a unique solution to the lighting of interiors from a particular era, but rather an array of possibilities. However, despite architectural variation and different levels of modern contamination between interiors, the range in lighting values obtained is actually quite narrow within any single era in the development of Gothic architecture.

These data suggests that in late thirteenth century grisaille programs, such as at Cologne, there is as much as double the total interior lighting available on cloudy days compared to full-colour window programs. Also, it is apparent that fourteenth century through Renaissance interiors provide as much as an order of magnitude more lighting on cloudy days than full-colour programs. At the same time, however, colour-dominated programs often supply similar interior illuminances under sunny conditions as fourteenth century and Renaissance interiors afford under cloudy conditions. Also, a preliminary survey of lighting in Renaissance Spanish cathedrals indicates that Mediterranean interior lighting under cloudy and sunny conditions is similar as in early thirteenth century cathedrals in the north (and in all cases analyzed much less than for northern Renaissance churches and cathedrals). Thus, our results confirm the assertion that full-colour programs may have been intended for sunny interior lighting, whereas grisaille-dominated and Renaissance programs demonstrate greater adaptability to cloudy conditions.

2 Evidence of a Transition to Cloudier Conditions in Northern Continental Europe between the Twelfth and Fifteenth Centuries

In order to investigate the nature of medieval sacred interior lighting aesthetic, it is first necessary to determine through other proxies how external illumination and cloudiness evolved during the Romanesque and Gothic eras in different parts of Europe. This is not an easy task given that few historical records pertaining to the weather are present during the Middle Ages, such records becoming more prevalent during and after the Renaissance (see Ogilvie, 1984 and Koslowski and Glaser, 1999). Cloudiness is also a difficult parameter to document without satellite imagery or a well-developed regional network of cloud observations, and these have only been realized in the second half of the twentieth century (see International Satellite Cloud Climatology Project, Warren et al., 2007). However, there are some proxy records from which we can make generalizations about medieval cloudiness, even if no single proxy gives an entirely complete picture of past cloud cover conditions over Europe. For example, humidity and precipitation proxies (from ombrotrophic bogs, speleothems, and tree rings) may be closely related to cloudiness; precipitation is particularly well-correlated to local nimbostratus occurrence and regional storm track. In addition, broad-scale temperature changes (tree rings, bore holes, and speleothems) can give indications of a mean shift in the position of the jet stream (and associated cloud-producing disturbances) to the north or south. Finally, atmospheric circulation patterns and related modes of variability (such as the North Atlantic Oscillation (NAO)) can be illustrated by a combination of different proxies to estimate mean jet-stream orientations, which can be further correlated to cloud patterns.

2.1 Explicit Cloudiness Proxies: Comets, Marine Cores, and Galactic Cosmic Rays

2.1.1 Comet Sightings

One of the few attempts to establish an historical record of cloudiness is provided by Link (1958), which is discussed extensively in Lamb (1985). Link uses the historical reports of the number of comet sightings, removing the trend of human skill, as a proxy for nighttime cloudiness back to the first millennium BC. The comet sighting reports are taken from sources in China and Western Europe, with the Chinese reports dominating the earlier historical records and European sources outnumbering the Chinese reports after 900 A.D. If we were to accept that the tendency during the central and later Middle Ages best represents Europe and that a sufficient number of records (and observers) were consistently available to establish a trend, then

Link's resulting cloudiness index does demonstrate low-frequency (200-400 year) oscillations in European cloudiness (thus, on a centennial time scale). In particular, there is a pronounced lull in cloud cover during the Medieval Warm Period (around 1100 A.D) followed by a substantial increase in cloud cover over the course of the thirteenth century, the time of the transition to the Little Ice Age. This dramatic increase in cloudiness, in turn, could justify an increasing awareness of cloudy-weather illumination in church interiors. Greater cloudiness before the turn of the last millennium also appears to correspond with the Early Medieval Cold Epoch, suggesting that colder periods in European climatic history may be associated on a very broad level with increased cloudiness over the continent.

However, Link's analysis, while perhaps providing a rough sketch of European cloudiness variation, still presents some severe limitations. For example, Link uses both Chinese and European comet reports together; however, if cloud cover conditions in the two regions are uncorrelated or anti-correlated then the two records have limited usefulness. In addition, human skill is difficult to estimate across the ages; for certain historical periods few records may survive, whereas in others many more records may be present, and in many cases observations were unwritten and reports were likely discarded over time. Also, the use of a proportionality constant, and generally the suitability of linear or exponential regression in describing the human skill factor, will always be disputable.

2.1.2 Planktonic Illumination Proxies

More recently, another illumination proxy (related to localized cloudiness) has been discovered through analyzing the $\delta^{13}C$ content of planktonic foraminifera such as G. Ruber found in shallow water sediment cores. Castagnoli et al. (2005) establishes that $\delta^{13}C$ in tree rings is best correlated with temperature, but in forams it is more sensitive to total illumination and solar forcing (presumably, as such, relating best to illumination during the growing season). In addition to observing solar radiation cycles (see Castagnoli et al., 2002), a shallow water core taken in the Gulf of Taranto appears to also represent decadal and longer-term average cloudiness. These data reveal a minimum in $\delta^{13}C$ (and maximum in cloudiness) during the Late Roman epoch, followed by a notable increase in $\delta^{13}C$ which culminates in a cloud cover minimum during the Medieval Warm Period around 1000-1200. These trends follow the proxy established by Link, which indicate a cloud cover maximum in the early medieval epoch and subsequent minimum during the Central and High Middle Ages. However, in the Castagnoli et

al. (2005) proxy, the Medieval Warm Period is followed only by a very slight increase in cloudiness during the Little Ice Age (in contrast to Link's broader-scale trend). This suggests that the transition from the MWP to the LIA was not severe in this part of the Mediterranean basin in terms of daylighting climatology, a possible explanation for the relatively continuous daylighting philosophy used in Mediterranean churches through the medieval period and into the Renaissance. A similar analysis of planktonic high-resolution shallow-water cores in other basins, such as the English Channel, the Baltic Sea, and the North Atlantic Ocean, might in the future provide useful long-term illumination information for other regions of Europe and thus demonstrate the contrasts in the evolutions of daylighting climate between the Mediterranean and Northern Europe.

2.1.3 Galactic Cosmic Rays

On the global scale, galactic cosmic rays (GCRs) have recently been identified as a mechanism that is strongly related to cloud cover variance on monthly and annual time scales. Furthermore, long-term proxy records of GCRs extending back to the Middle Ages are available. Svensmark and Friis-Christenseen (1997) demonstrate that the correlation between midlatitude cloud cover and GCRs is as high as $r = 0.97$, and the coefficient remains relatively constant when applied to a variety of satellite data (this is especially true for oceans and maritime regions). In general, because GCRs decrease (increase) during periods of enhanced (relaxed) solar activity, it is probable that the close cloud cover-GCR flux correlation is related directly to microphysical interactions between GCRs and CCNs (see Tinsley and Yu, 2004) or indirectly through a mechanism more closely associated with the intensity of solar irradiance. Furthermore, Marsh and Svensmark (2000) demonstrated that low clouds, which often limit exterior global illumination at the surface better than high clouds, are best correlated with GCR fluxes compared with other cloud types. In this case, some of the best correlations are over the North Atlantic, the British Isles, Western France, and the Mediterranean basin. A possible microphysical explanation for a low cloud correlation with GCRs is given by the ion-mediated nucleation hypothesis given in Yu (2002) and Tinsley and Yu (2004). This process may also lead to decreased precipitation, greater optical thickness and cloud albedo, and thus decreased available illumination at the surface. Tinsley and Deen (1991) and Tinsley and Yu (2004) also link GCR fluxes and North Atlantic storm track latitude. They suggest that an interaction between microphysical processes, latent heat transport and vorticity supports frequent western Atlantic

storm track cyclogenesis, weakens baroclinicity in the Eastern Atlantic and contributes to the negative NAO pattern over Europe on decadal time scales.

Tinsley and Yu (2004) were also one of the first studies to use GCR fluxes on decadal and longer term time scales to analyze cloudiness and storm track variance. Additionally, McCracken and McDonald (2001) demonstrated a strong correlation between ^{10}Be deposition and cosmic galactic rays since measurements began in the 1930s. They used these isotopic records to hindcast GCR fluxes back to the beginning of the Little Ice Age.Taking these data, Mendoza et al. (2004) explored the ^{10}Be -cloud cover relationship to evaluate potential impacts on temperature. Further records of ^{10}Be are provided in Bard et al. (2000) back to the Early medieval period; these document a strong inverse relationship between solar activity (recorded in the δ^{14}C proxy) and ^{10}Be, a relationship comparable to GCR-solar irradiance anti-correlations on shorter time scales (see Figure 2.1). The proxy record also suggests that GCR fluxes on long time scales were likely at a pronounced minimum between 1100 and 1200 A.D., possibly indicating reduced global cloudiness. A broader lull in GCR fluxes can be identified from 1200 A.D. back to the beginning of the record in 850 A.D., interrupted only briefly during the Oort solar minimum around 1050 A.D. After 1200 A.D., however, a nearly continuous increase in ^{10}Be production is documented, reaching its highest level during the record by 1450 A.D and continuing, with a brief interruption between 1500 and 1600 A.D., through the Maunder Minimum (around 1650-1700 A.D). These higher GCR fluxes likely would have accompanied conditions that supported a prolonged period of enhanced cloudiness and perhaps a southward-shifted mean jet position over Europe.

In general, the possible proxy provided by GCR fluxes appears to corroborate well with Link's comet analysis (as well as NAO indices discussed below), with a minimum in cloudiness during the Medieval Warm Period and a possible increase before the onset of the Little Ice Age. However, despite the low-level cloud correlations with GCRs in regions of the Eastern North Atlantic and Europe, it is difficult to make any conclusions on European trends based on Antarctic data (more local ^{10}Be representations or correlations between European and Antarctic ^{10}Be production associated with GCRs may be more appropriate). Additionally, a universally-accepted physical explanation between the GCR-cloud cover variance relationship has yet to be found, and the GCR relationship currently appears to work best on a global scale and cannot distinguish regional cloud cover variances at this time. Because cloud formation is often

determined by local ionization processes and aerosol availability, further research needs to be done to determine the relationship between localized long-term isotopic ^{10}Be concentrations and recent direct GCR measurements in different parts of Europe and their respective correlations with recent regional cloudiness before it can be used as a more definitive proxy for European cloud cover trends in the past.

2.2 Precipitation Proxies

Storm tracks and associated cloudy weather are also often accompanied by precipitation. While clouds do occur quite frequently without precipitation, precipitation does not occur without clouds, and therefore high and low precipitation anomalies can also be used as an indicator of the prevalence of precipitation-producing clouds such as nimbostratus and cumulonimbus and their associated storm systems. Other clouds types, such as stratus, fog, and middle and high level clouds, which can be an important part of the total cloud climatology, are not directly represented in precipitation indicators. Despite these drawbacks, a variety of precipitation-related climate proxies are available, including peat bog stratifigraphy, speleothems, tree rings in arid regions, and glacial mass balance fluctuations (see Barber et al., 2004b). Evidence from these proxies on the climate of Europe during the medieval and Renaissance periods are discussed below.

2.2.1 Peat Bogs: Warm Season Effective Precipitation

Several climate proxy reconstructions are available from peat analyses of ombrotrophic (exclusively rain-fed) bogs in parts of northwestern Europe that provide a direct link to long-term evaporation minus precipitation (henceforth referred to as effective precipitation) variability (Barber et al., 2004a). A variety of methods for determining past climatic wetness can be applied to peat cores, such as peat humification, macrofossil counts and testate amoebae analysis; all of them are dependent on the prevalence of wet-indicating versus dry-indicating species (or rates of decomposition) that contribute to the bog's underlying peat layers. Because many of these measures depend on plant production, it is believed that the precipitation indices derived from them are more closely related to summer effective precipitation (bog levels during the growing season) rather than winter precipitation (Barber et al., 2004b). In addition, because effective precipitation is influenced by evaporation, the climate signals derived from peat bogs are also believed to be partially influenced by temperature rather than exclusively by precipitation. Thus, low bog wetness could indicate dry and/or warm conditions. Barber et al. (2004b) considers the

Polar Front, and thus the prevailing storm track, to be the likely predominate influence on bog surface wetness. Peat bog analysis is often constrained to parts of northwestern Europe, as rain-fed bogs require a wetter climate that is not available in the Mediterranean or even in central Europe. Additionally, the sensitivity of ombrotrophic bogs to precipitation has been shown by Haslam (1987) to deteriorate when moving from west to east and from north to south across Europe, thus limiting most studies to Denmark, Northern Germany, and the British Isles.

Aaby (1976) established one of the first peat bog climatologies for a core in Denmark and concluded that effective precipitation trends closely followed the temperature patterns indicated by Lamb (1965). In particular, he found that change in peat formation associated with a wetter climate began in mid-thirteenth century and culminated in the sixteenth century, indicating a likely year-round (and particularly a summer) displacement of the jet stream further south over northwestern Europe during the LIA (providing wetter and cooler conditions). Similarly, Barber et al. (2004a) covered the same area, i.e. Denmark and parts of northern Germany, and obtained similar results, with the bogs showing a prominent shift to wetter and/or colder conditions between 1250 and 1350 A.D. Similarly, peat humification records in Baker et al. (1999) also appear to indicate wetter conditions between 1600 and 1850, as well as between 1400 and 1500 in northwestern Scotland, corresponding to the heart of the Little Ice Age—the Spörer and Maunder minima. In bogs in northern Ireland and Scotland, despite floral differences between the two sites, a detrended correspondence analysis revealed a peak in dryness around 1180 to 1200, followed by a sharp increase in wetness thereafter, continuing through the fifteenth century (Barber et al., 2000). Similarly, Langdon et al. (2003) demonstrates a drier and/or warmer medieval Warm Period between 1000 and 800 cal. BP and a climatic deterioration thereafter.

Even more peat cores have been obtained in the British Isles. Chiverrell (2001) did a study of a core from May Moss near York, England and demonstrated similar trends, such as shifts to wetter or colder periods between 1350 and 1450 cal. A.D. and 1400-1620 cal. A.D. He also provided evidence of a drier climate between 1000 and 1100 A.D. and the transition to the Little Ice Age thereafter. Such conditions were also seen in other peat records in Northern England and Southern Scotland. Mauquoy and Barber (1999), contrary to other studies, demonstrated times of increased effective precipitation and bog wetness during the periods 920-1060, 1110-1260, and 1460-1470 cal. A.D in two bogs in northwest England. The interval of

greatest wetness, namely 1110-1260 cal. A.D. corresponds broadly with the time of wetness increases in southern Wales between 1150 and 1200. The Little Ice Age, according to Maquoy and Barber (1999), was both more variable and drier than the Medieval Warm Period, perhaps due to a local climate signal or storm track displacement further to the south or north.

Some of the inconsistencies between the datasets are due to different methods of radiocarbon dating between the peat bog samplings and the larger dating uncertainties (as much as a century) in their methodologies, although in the future wiggle match dating may provide greater accuracy in peat chronologies (Barber et al., 2000). For these reasons, ombrotrophic bog records are unable to be incorporated into a broader-scale multiproxy climate reconstruction as is the case for tree rings and speleothems (which have annual or nearly annual resolution and greater dating accuracy in most cases). In addition, local effects, such as elevation (as suggested in Barber et al., 2000) and local precipitation effects, may provide a microclimate record that is at odds with other records taken on a broader scale (which may be the case with Maquoy and Barber, 1999). For example, upland precipitation in northwest Scotland may follow the annual trends seen in Proctor et al. (2000) and thus may be more closely related to the winter North Atlantic Oscillation (Langdon and Barber, 2001; Langdon and Barber, 2005). Despite these difficulties, Table 2.1, taken from Barber et al. (2004a), demonstrates that virtually all studies document a wet-shift, a period of rising bog water levels, between 850 and 600 years B.P. This appears to be a remarkably consistent transition across the records, similar to that of the Early Medieval Cold Epoch (which shows an almost universal significant rise in greater effective precipitation around 1400 years B.P., coincident with the transitions also described in Link (1958) and Castagnoli et al. (2002)). This also corroborates with our suggestion that a notable climate shift occurred over the course of the Gothic era (also between 850 and 600 years B.P.) and provides impetus for an analysis of architecture within the framework of this transition.

In addition, a comparison of these proxies with Proctor et al. (2000) seems to confirm Barber et al. (2004b)'s claim that peat bog and related analyses are likely best related to summer precipitation, which is sometimes contrary to winter precipitation patterns. The effective precipitation trend for the bog in northwestern Scotland (documented by Baker et al. (1999)) appears to oppose Proctor et al. (2000)'s speleothem precipitation record (where the temperature trend was removed), which shows less rain during the LIA and more precipitation during the MWP. In the winter, the North Atlantic Oscillation, defined more rigorously below, provides a

good indicator of storm track position and related areas of precipitation (an active storm track over Scotland and Scandinavia during strong positive phases in the NAO and a weaker storm track over southern and central Europe during negative NAO phases). Winter precipitation (December to March) in northwestern Scotland, as discussed in Hurrell (1995), is strongly correlated ($r = 0.77$) with the winter North Atlantic Oscillation index. The annual precipitation record provided in Proctor et al. (2000) similarly correlated at $r = 0.70$ with the winter NAO index, attributing half of the annual precipitation trend in the proxy to variations in the NAO alone. The effective precipitation maxima seen in the bog humification record during the Little Ice Age appear to contradict the decreased precipitation expected during the winter from Proctor et al. (2000), with a predominately low NAO index during extended periods of the LIA. The possible persistence of a low-index NAO pattern during the Maunder Minimum in particular and LIA in general is observed in a variety of well-respected, instrument and proxy-based reconstructions of the NAO that also cover the peat bog record period (see Cook et al. (2002), Luterbacher et al. (1999), Luterbacher et al. (2001a), Luterbacher et al. (2001b), and Proctor et al. (2000)). In other words, during the LIA Proctor et al. (2000) would mandate less precipitation in Scotland, likely because of a southward-displaced winter jet (which is also suggested by the generally colder conditions seen during this time period). The other bogs throughout northern England, southern Scotland, and Denmark are located within a relatively narrow latitude band across western Europe where effective winter precipitation is positively correlated with the NAO index (see Hurrell 1995, Reichert et al., 2001). If bog levels as recorded in the peat proxies represented winter precipitation, then one would expect a relatively drier LIA and wetter MWP as indicated by the above mentioned proxy reconstructions.

The opposite trend is observed in the peat record; however, this makes sense in the context of summer precipitation, as a southward-displaced jet over central and southern continental Europe during the winter would likely migrate north during the summer to affect the latitude band represented by the peat bog record. The corresponding cooler and wetter conditions, with greater cloudiness, would in turn minimize summertime evaporation (when this contribution would likely be strongest). On the other hand, for a persistently high NAO winter pattern, one would expect a strong jet positioned over the British Isles during the winter to be shifted further north or otherwise weakened during the summer with the warm season expansion of the subtropical high, leading to drier conditions over the British Isles (and a drier peat bog

wetness). The peat record thus appears to indicate a transition from the latter case to the former, a shift of the subpolar jet stream during the summer LIA months to a mean position where more synoptic-scale storms affect the British Isles and perhaps also locations further south. Greater summer cloudiness during much of the LIA is not inconsistent with Lamb (1985), which similar to this thesis attempted to understand historical cloudiness through the lens of human aesthetic. It appears that many Dutch and English artists portrayed mostly cloudy landscapes until the twentieth century (Lamb, 1985).

On the other hand, warmer and drier summer conditions appear to be relatively consistently observed in the MWP across many bogs, suggesting that the summer storm track was shifted away from the British Isles. If it has been positioned nearer to the British Isles under the declining summer temperatures (Briffa et al., 1992, Fig. 8; Büntgen et al., 2006); Kirchhefer, 2001) and declining annual temperatures (Hegerl et al., 2007; Jones et al., 2001; Luterbacher et al., 2004; Mann et al., 1999) documented during the transition from the Medieval Warm Period to the Little Ice Age, the storm track would have likely been shifted to the north of the British Isles (or weakened) during MWP summers. Therefore, peat bogs provide a particularly insightful representation of effective precipitation trends, as they illustrate centennial-scale oscillations associated with (primarily) warm-season precipitation patterns (as discussed in Barber et al. (2004b)) and their associated storm track positions. These summer patterns are not well represented by the NAO index, which is often poorly defined and shows low to no significant correlations with precipitation in the summer months (Qian et al., 2000).

2.2.2 Speleothems: Stable Isotope Records and Annual Banding

Speleothems taken from caves overlain by peat can also be a particularly useful climate proxy. Their isotopic records of $\delta^{14}C$ and $\delta^{18}O$ provide resolutions nearly equivalent to those of ice cores (such as those from Antarctica and Greenland), but at the same time they offer information that is more relevant to regional climate signals in Europe. Annual growth banding was introduced as a climate proxy record in Baker et al. (1993), and evaluations of stalagmite luminescence has also provided a high resolution record of precipitation. Most stalagmite proxy records have both a temperature and precipitation component present in their stable isotope record. Further complicating factors are discussed more thoroughly in Frisa et al. (2005) and McDermott et al. (1999). On the other hand, annual band translucency (Niggemann et al., 2003) and growth rate (Proctor et al., 2002) are primarily influenced by peat humification and

associated calcium ion leeching above the cave, thus providing a closer link with precipitation processes (high effective precipitation is associated with reduced soil respiration and thus low PCO_2 production and slower speleothem growth rates).

Proctor et al. (2000) was one of the first studies to provide a precipitation-only proxy derived from a speleothem from a cave in northwestern Scotland. The resulting precipitation index, seen in Figure 2.2, is reported in absolute terms (mm), and it reveals that precipitation in Scotland generally peaked during the Medieval Warm Period between 900-1300 A.D. (with a marked but short-term decrease during the Oort Minimum). This was followed by a sharp decrease and regime shift after 1300 A.D., with precipitation continuing at lower average levels through much of the Little Ice Age. These results were also discussed in Proctor et al. (2002) through the presentation of the absolute growth rates of the speleothems at hand. Because the NAO index and precipitation in northwestern Scotland are so strongly linked, Proctor et al. (2000) suggest the use of their absolute precipitation index as a NAO proxy. This would indicate a higher NAO (and more northward-displaced winter jet) during the MWP and lower NAO (southward displaced jet) during the LIA. The associated pattern would imply long-term centennial or multidecadal fluctuations in mean jet latitude and support the claim that greater cloud cover was present over the British Isles but fewer clouds over France and the Mediterranean during the MWP. Proctor et al. (2000)'s consequences for NAO phase frequencies and related covariance with cloud cover are further discussed below.

Isotope records for various speleothems throughout Europe are also available and can reveal regional climatic differences, making this proxy one of the few climate indicators that can be directly applied simultaneously to all regions concerned in this study. However, they are also strongly influenced by temperatures, and applying the methods provided by Proctor et al. (2000) might be appropriate to obtain a temperature-only or precipitation-only signal from the data. The separation of these effects, however, may prove extraordinarily difficult when evapotranspiration and site-specific factors are large such as in Mediterranean samples (McDermott et al., 1999). Baker et al. (2000) and McDermott et al. (2001) present results from Crag Cave in southwestern Ireland, which demonstrates that higher $\delta^{18}O$ values (suggesting warmer temperatures and/or drier conditions) were present during the Medieval Warm Period, followed by a sharp decline around 1200 A.D., coincident with the beginning of the Gothic era in architecture. These results are also consistent with isotopic signatures determined from Greenland Ice cores (McDermott et

al., 2001). Far across the continent, a stalagmite taken from a cave in Sauerland, Germany (northeast of Cologne) demonstrates the same trend, with an extended peak in $\delta^{18}O$ and $\delta^{14}C$ between 1000 and 1200 A.D. followed by a sharp drop (particularly severe in the $\delta^{18}O$ record) between 1200 and 1300 A.D (Niggemann et al., 2003). A few rapid oscillations in $\delta^{18}O$ are present during the LIA, but they never achieve, and together average well below, the MWP peak (Niggemann et al., 2003, Fig. 8). In addition, while $\delta^{18}O$ levels remain low through the LIA, $\delta^{14}C$ actually increases substantially (in oscillatory stages) after 1200 A.D. to two peaks nearly corresponding to the Maunder and Spörer minima, suggesting that drier winters were probably more common in central Europe during the LIA (Niggemann et al., 2003)

McDermott et al. (1999) provided a more regional analysis and indicates that, throughout the Holocene, there has been significant decoupling between Mediterranean and North Atlantic climates, particularly on the centennial scale (McDermott et al., 1999, Fig. 6). The two Mediterranean caves (one in southern France and another in northern Italy) both show an increase in $\delta^{18}O$ after 1200 A.D., which suggests warmer and/or drier conditions. At the same time Crag Cave sees decreasing values (becoming, on average, cooler and/or wetter) (McDermott et al., 1999, Fig. 4). This suggests that the Mediterranean climate was not deteriorating in the same manner as that of northwestern Europe during the Gothic era. Similarly, a speleothem climate reconstruction (Frisa et al., 2005) using $\delta^{18}O$ from Grotta Savi near Trieste, Italy shows a more complex climate not following the typical MWP and LIA variations seen in northern European proxy data; instead, it demonstrates an Early Medieval Cold Period (documented in the marine core discussed above) around 600-700 A.D., followed by a Medieval Warm Period (800-1000 A.D.), a second, slightly less pronounced Medieval Cold Period (900-1100 A.D.), followed by a second Medieval Warm Period (1150 – 1400 A.D), followed by the LIA, which becomes more and more pronounced between 1500 and 1800. This is corroborated by Serre-Bachet (1994)'s tree ring temperature reconstructions of northeastern Italy, which demonstrate a broadly mild medieval climate in the Mediterranean up to 1500 A.D., with the only substantially warmer epoch recorded in the late fourteenth and early fifteenth centuries.

These results led the author to conclude that the "climatic deterioration from 1300 on reported by several authors for northern Europe is not really found." Alexandre (1987) provides similar findings, with a warm peak evident in southern Europe in the fourteenth century (Hughes

and Diaz, 1994), and Chapron et al. (2002) also argues that the sector of Europe most influenced by the LIA "had its southern boundary in the Alps." Therefore, speleothem and tree ring data appear to show a slight shift in the Mediterranean climate by the time of the Maunder minimum; however, there is a lot of variability in the medieval climate so that no clear cooling or increasing precipitation trend is evident during the Gothic era as seen in northern Europe. This would appear to support the suspected lack of dramatic change in total global illuminance available in Mediterranean regions as indicated in Castagnoli et al. (2005), and therefore a relatively constant interior daylighting aesthetic would be expected from a climatic perspective.

2.2.3 Tree Ring Reconstructions

Another potential precipitation proxy can be provided by tree rings. While many methods centering on Maximum Latewood Density and ring thickness have been applied to temperature measures in a mid-latitude setting, in extremely dry climates with relatively mild year-round conditions pine dendrochonology series have shown to be most sensitive to precipitation (Till and Guiot, 1990). Morocco, near to the Western Mediterranean climate regime of Europe, qualifies as such an environment, and Till and Guiot (1990) have documented average annual precipitation (most of which falls during the autumn, winter, and spring) using tree rings from a variety of pines taken from three subclimate regimes differentiated by their aridity. They determine that the precipitation over Morocco does not show a clear trend during the LIA, with both pronounced wet and dry periods occurring throughout the climatic epoch. At the same time, all three subclimates demonstrate a substantially arid period in the late twelfth and early thirteenth century, followed by a jump in precipitation from the early thirteenth century until the fourteenth century, reaching levels that were largely unprecedented in the century before and rarely obtained afterward for such a sustained period (see Till and Guiot, 1990, Figs. 3, 4). It should be noted, however, that precipitation is still very low in absolute terms through all periods (still providing a typically Mediterranean climate regime).

Therefore, while no consistent LIA trend is present, again it is possible to identify a notable climate transition occurring in the thirteenth century that suggests a possible increase of storm system incursions (likely during the winter) into to the southern Mediterranean basin (Chapron et al., 2002), corresponding broadly to the summer wet shifts seen at the same time in peat bogs in northwestern Europe. Thus, the Morocco tree ring proxy suggests that greater storminess over continental Western Europe may have been a significant concern by the

thirteenth and fourteenth centuries. In addition, a similar tree ring precipitation record reconstruction from Brittany demonstrates that for warm periods in the previous four centuries, drought occurrence in Brittany was doubled (Masson-Delmotte et al., 2005), possibly indicating also that the warmer epoch demonstrated by speleothems and tree rings before 1200 A.D. in northwestern Europe may have been accompanied by more dry weather events in western France under a regime dominated by a northward-displaced jet stream.

2.3 The NAO: Winter Cloudiness Variability

The North Atlantic Oscillation (NAO) index, defined by the normalized sea level pressure (SLP) difference between the Azores (or nearby Gibraltar or Lisbon) and Iceland (i.e. P_{Azores} - $P_{Iceland}$), is another tracer that can be used to track cloud cover over the European continent and climatic variability on long time scales. The NAO is one of the dominant modes of climatic variability in the Northern Hemisphere; it demonstrates the best correlations to climate parameters (pressure, precipitation, temperature, etc) in the winter months, but its signal exists yearround. According to Hurrell (1995), a high (positive) NAO index is associated with a stronger zonal jet (concentrated between Iceland and Scandinavia), southwesterly flow across Europe, and greater precipitation in the northern British Isles and Scandinavia (and less precipitation in the Mediterranean and much of France and central Europe). During a low (negative) NAO index, cyclonic activity in the eastern Atlantic basin decreases, the subpolar jet weakens and shifts south, temperatures decrease across much of Europe, and precipitation often increases in the Mediterranean and central Europe (Hurrell, 1995; Trigo et al., 2002). For example, Tiree station in northwestern Scotland has a NAO-precipitation correlation of $r = 0.68$, and for Bergen it is $r = 0.77$, whereas Paris and Frankfurt (an axis of interest for this study) have precipitation correlations of $r = -0.18$ and Lyon $r = -0.37$ (becoming more negative closer to the Mediterranean basin). Due to these relationships, the NAO has often been used as a measure of mean latitudinal variation in storm track (see Hurrell, 1995). Even though multidecadal storm track variability does not always follow NAO patterns, it often correlates with them (see alternative regimes used by Rogers, 1997 and Chaboureau and Claud (2006)). Therefore, while the NAO may not be the perfect measure of climatic (and cloud) variability over Europe (as neutral NAO regimes may be associated with maximized cloudiness in northern continental Europe), it often adequately represents the latitudinal climate variation, and cloud cover climatology across Europe also follows a latitudinal gradient (Meerkötter et al., 2004). In

addition, several proxy records have been used, based on regional variations in temperature and precipitation (as they correlate with the NAO), to estimate NAO indices back to the Little Ice Age (see Cook et al. (2002), Luterbacher et al. (1999), Luterbacher et al. (2001a), Chapron et al. (2002), and Glueck and Stockton (2001)) and even the Medieval Warm Period (see Proctor et al., 2000 and Brutckner and Mackensen, 2006). Therefore, the NAO provides us with a unique opportunity to evaluate likely winter cloudiness distributions, as a counterpart to our summer precipitation analysis (and relationship to jet stream position) during the Gothic era. In addition, NAO and cloud cover relationships are also particularly relevant to architectural studies, as results from our analyses indicated that the interior lighting differences between cloud and sunny conditions are most extreme during the winter.

2.3.1 NAO and Cloud Cover Relationships

Fortunately, a variety of studies have already been performed on European cloudiness and its relationship to the North Atlantic Oscillation. Sizov (1997) concluded in his limited-scope interannual NAO variability study that decreases in cloudiness in the 40-50° latitude belt in Europe were often associated with increased values of the NAO index, and that the NAO appeared to control as much as 7-10% of the cloud coverage variability in Europe. The area of decreasing cloudiness corresponds broadly to our area interest in the development of Gothic interior lighting aesthetic. In addition, Previdi and Veron (2007) also document cloud cover changes associated with the NAO (although mostly in the North Atlantic Ocean away from the European continent), and their study indicates that some of the greatest cloud cover forcing (measured by decreased shortwave radiation and increased longwave radiation at the surface) for high NAO index months is particularly substantial over the British Isles (especially the northwestern sector of the British Isles and Western Norway) (Previdi and Veron, 2007, Fig. 7). Also, the cloud cover forcing related to positive NAO index values also appears to drop off strongly in southern England and correspondingly over France. Additionally, monthly cyclone frequency also increases greatly in a swath from the central North Atlantic south of Greenland to Svalbard for positive NAO periods (Previdi and Veron, 2007, Fig. 5), thus documenting the substantially increased occurrence of cyclones (and associated cloud masses) that track well north of the European continent during high NAO regimes. Chaboureau and Claud (2006) provide an exclusive analysis of cloud cover variance in the Mediterranean basin, which reveals that total Mediterranean cloud systems per day decreases with increasing NAO index

(particularly in the northeastern and northwestern Mediterranean basin). However, as can be seen in Chaboureau and Claud (2006, Fig. 9), the total number of cloud systems per day present in the Mediterranean throughout the analysis period is never extremely large, even for very low NAO values.

In contrast to the more regional analyses provided above, Warren et al. (2007) affords a more pan-European perspective on winter NAO-cloudiness correlations. Compiling over two decades of observational cloud reports and correlating them with the Northern Annular Mode (NAM) of sea level pressure variability (the first EOF of sea level pressure, analogous to the NAO), the variation of specific cloud types with the NAO can be determined across Europe. Since the record began, much of Western Europe has seen a decreasing linear trend in total cloud cover, particularly prominent in the Mediterranean basin (Warren et al., 2007, Fig. 10), whereas Norway, inland Russia, and parts of northwestern Scotland saw an increasing trend. This is perhaps not surprising given the switch from predominately negative to strongly positive NAM index values during the analysis period (1971-1996). Correspondingly, Henderson-Sellers (1986) reveals increasing total cloud cover over continental Europe when moving generally from a high to low winter NAO phase.

Warren et al. (2007)'s comparison of nimbostratus variance with NAM indices, shown in Figure 2.3, demonstrates a very strong negative correlation across much of continental Europe, particularly significant in Spain, southern France, and Italy. The strong negative correlations between nimbostratus occurrence and the NAM index in eastern Scandinavia may seem relatively surprising given the expected jet position, but not within the context of Scandinavian orography. This is illustrated by weakly positive correlations of precipitation in Oslo ($r = +0.20$) and Helsinki ($r = +0.18$) with the NAO index at roughly the same latitude as Bergen ($r = +0.77$). This discrepancy is likely attributable to enhanced moisture leeching along the Norway's west coast mountains and associated leeside effects seen in the Baltic. Thus, much of the nimbostratus correlations for eastern Scandinavia and part of the Baltic coastline likely derives from the fact that, if the jet were positioned further south so as not to intersect the Norwegian mountains (a slightly positive or neutral phase of the NAO), then more cloud cover and precipitation would be available than for a very high NAO trend where the jet and associated moisture transport are transected by the Norwegian mountains. This important 'mountain factor' on Scandinavian cloud cover is confirmed by the results seen in Previdi and Veron (2007), and therefore greater

cloud cover in eastern Scandinavia would not necessarily be expected with a very low NAO index (thus, we consider the negative correlations in the Mediterranean and Western Europe to be the most important). Positive correlations between nimbostratus and NAO index are mostly constrained to the northwestern edge of Europe (again, northwestern Scotland and coastal Norway), suggesting that these prominent rain-producing clouds and their associated isentropic lift-associated cloud band become more numerous further to the north away from continental Europe during positive NAO decades.

This relationship between high nimbostratus correlations and subpolar jet cloud band prevalence also seems to corroborate with the Eleftheratos et al. (2007) correlations between NAO and cirrus cloud mass (also most often associated with overrunning patterns during the midlatitude winter). Their data shows the greatest positive NAO-cirriform cloud cover correlations to the north of the British Isles, co-located and to the northwest of the areas demonstrating the greatest nimbostratus correlations in Warren et al. (2007). The two studies together thus provide an indication of where we could expect to most frequently observe a polar front (overrunning) cloud band during positive NAO winters (likely in a southwest to northeast-oriented band with its southern edge near the British Isles and cirrus cloud shield extending over the Atlantic to the northwest) and during negative NAO winters (a band more often located in central or southern Europe).

Because nimbostratus and cirriform clouds only provide part of the story, Ryan Eastman from the University of Washington (Seattle) has generously provided us with NAM-cloud cover correlations over Europe for other prominent cloud types that severely limit available surface illuminance, such as stratus (Figure 2.4a) , fog (Figure 2.4b), and altocumulus (Figure 2.4c). The stratus and fog show weak positive correlations to the NAM index isolated largely to northern France, with values generally varying between 0.2 and 0.6 (fog shows greater variance, and stratus may well be a reflection of lifting fog). This weak trend may be explained by the increased prevalence of winter morning fog associated with weak high pressure regimes south of the main subpolar jet. Heading north from France, faint negative correlations with the NAM over England followed by positive correlations in northwest Scotland suggests that the greatest variance in stratus clouds associated with jet overrunning patterns is likely co-located with those of nimbostratus. Mediterranean stratus clouds appear to possess negative correlations with the NAM index as well. There are weak positive correlations between NAM and fog in the

Mediterranean basin; like in France these correlations might be positive due to nighttime radiative winter cooling and lower minimum Mediterranean temperatures seen during positive NAO phases, suggested by Trigo et al. (2002, Fig. 4c)

More interestingly, altocumulus clouds (a mid-level cloud indicator) show much stronger negative correlations (r = -0.4 to -0.8) over much of continental Europe, a trend that is strongest in northern and central France and weaker in the Mediterranean basin and over the British Isles. Coupled with the correlations provided by nimbostratus (which show some of their greatest negative correlations just south of the strong mid-level cloud correlation band), one can deduce that cloud bands associated with negative NAO patterns are not only broader but cover much of Europe. In other words, low-index NAO overrunning patterns produce more nimbostratus in the Mediterranean (Spain, Italy, and southern France) and more mid-level cloud cover just to the north over central and northern France. In addition, the broadness and strength of the NAM nimbostratus and altocumulus cloud cover correlations across much of Europe suggests that negative NAO patterns, associated with a weaker zonal jet, are probably more closely associated with broader, more dispersed, less strongly organized cloud bands associated with weaker storms (common during low NAO) that can affect broader areas of Europe (these cloud band orientations are discussed further in Kidder and Vonder Haar, 1995). By contrast, a strong positive NAM index appears to accompany significant cloud cover only for a very restricted section of northwestern Europe and less cloud cover elsewhere; thus, contrary to the diffuse, broad cloud cover potential of low NAO regimes, a high NAO represents an intense, organized jet pattern where extensive cloud bands are generally more closely constrained within a narrower region along the jet and north of the jet). It should be noted that these correlations are site-specific; parts of the Mediterranean are likely to still receive less annual cloud cover than parts of central and northern Europe during a negative NAO. Because the Mediterranean climate by definition is relatively dry and sunny for much of the year, even a small increase in cloudiness may provide significant correlations in the Mediterranean, whereas in northern Europe where cloud cover is climatologically prevalent the correlations may represent a larger, more perceivable change in total cloudiness. Given the indicators presented above, we would suspect the greatest cloud cover over France and central Europe to occur during negative or neutral NAO regimes and to be severely limited during strong positive NAO regimes (where the primary overrunning cloud band's average position shifts to the north over the British Isles and Norway).

2.3.2 NAO Proxies and Related Indicators

Given the remarkably complete picture available for the decadal relationships between NAO and European cloud cover, it would be particularly useful if we could determine past NAO indices that demonstrate multidecadal and centennial NAO cycles, which would establish definitive long-term winter cloudiness regimes on the time scales suggested of the summer storm track patterns seen in the peat bog proxies. While NAO multidecadal and longer-term variability is still heavily debated, and not all proxy constructions (based on the way that they are correlated) can reproduce low frequency variability (see Cook et al. (2002) and Hegerl et al. (2007) for a discussion of these issues), several long-term NAO cycles have been identified. In particular, 50-68 year, 80-90 year, and 212 year statistically-significant frequencies have been observed by some authors (Chapron et al., (2002), Luterbacher et al. (1999)). While longer records may be needed to establish whether or not a true multidecadal oscillation occurs (Proctor et al. 2002), low frequency variation in the NAO index does appear to be a feature of the medieval period. Shindell et al. (2001) has also demonstrated multidecadal-to-centennial time scale NAO/AO frequencies associated with positive feedbacks related to solar irradiance variations (which do vary on centennial time scales), with a possible connection to forcing from tropical SSTs. Tinsley et al. (2004) has also indicated that long-term NAO patterns (positive vs. negative) are likely phase-locked to solar variability, a theory also discussed with respect to the Middle Ages in Bradley et al. (2003).

In addition, Bochníček and Hejda (2006), Gimeno et al. (2003), Georgieva et al. (2007), Kirov and Georgieva (2002), Kodera (2002), Lukianova and Alekseev (2004), Palamara and Bryant (2004) and Thejll et al. (2003) also address important solar variability-NAO correlations on annual, decadal, and multidecadal time scales. The exact mechanism for this relationship is still debated, but correlations have been proven stronger for specific Quasi-Biennial Oscillation (QBO) phases (Bochniček and Hejda, 2006; Palamara and Bryant, 2004) and solar irradiation thresholds (higher sunspot numbers) (Lukianova and Alekseev, 2004). In general, increased solar activity is associated with increasingly positive NAO values (Georgieva et al., 2007). For example, Boberg and Lundstedt (2002)'s analysis of group sunspot number and NAO phase indicate that important solar minima are apparent in averaged NAO index values between 1610 and 1976, with a correlation of $r = 0.56$. In addition, Usokin et al. (2003), reconstructing sunspot numbers based on proxy records from Antarctic cores (provided in Figure 2.1), reveals that the

Medieval Warm Period from 1100 to 1250 maintained the longest period of sustained high solar activity (averaging 40-50 sunspots) in the past 1150 years, at levels comparable to those in the 1940s in Lukianova and Alekseev (2004) when a dramatic improvement in NAO-solar variability correlations were observed. Given the persistence of the high solar irradiation during the twelfth through early thirteenth centuries, not only higher solar-NAO covariances but also more positive NAO events might have occurred.

This relationship between solar irradiance variability and the North Atlantic Oscillation seems quite plausible in the reconstructed northwestern Scotland precipitation records in Proctor et al. (2000). As indicated earlier, precipitation in northwestern Scotland possesses strong positive correlations with the NAO index, and Proctor et al. (2000)'s record (see Figure 2.2) demonstrates remarkable agreement with global solar irradiation trends (see Bard et al. (2000) and Figure 2.1). In particular, the Central Middle Ages (900-1200) belongs to a relatively high precipitation regime, except for a sharp drop (with a decadal lag) corresponding to the Oort Minimum (1060), and similarly precipitation shows decreases corresponding to the Wolf, Spörer, and Maunder minima in solar irradiance (labeled W, S and M in Figure 2.1). The lag effect may also demonstrate that long-term NAO phases are linked, as suggested by Shindell et al. (2001), to solar variability through ocean processes (see also Kushnir, 1994). However, the Oort minimum is the most pronounced solar variability-related anomaly in the precipitation record, which may be a product of greater NAO-solar activity synchrony during periods of higher solar irradiance.

Using Proctor et al. (2000) as a general indication of NAO phase (as the author does), it does appear plausible that the NAO can undergo a multidecadal to centennial cycles (and did during the medieval period) and that the thirteenth century in particular demonstrated an especially high positive-phase NAO regime (corresponding to less winter cloud cover over continental Europe), followed by a dramatic transition to lower NAO indices around 1300. Furthermore, the record not only indicates substantial variation in NAO sign over the course of the LIA but also suggests that LIA NAO indices were, on average, significantly lower than in the twelfth and thirteenth centuries (particularly pronounced during the solar minima). The precipitation index in Scotland also appears to reflect Luterbacher et al. (2001b), Koslowski and Glaser (1999), and Wanner et al. (1995)'s claims that prolonged periods of the cold LIA

European climate, such as seen during late Maunder minimum, was likely dominated by a low-index NAO pattern lasting as long as several decades at a time.

Another NAO reconstruction provided in Brutckner and Mackensen (2006) extends back to the Medieval Warm Period and also appears to confirm a strong shift in NAO index around the end of the thirteenth century as seen in Proctor et al. (2000). The authors use a correlation between Skagerrak basin deep water temperature and NAO sign, along with the existing benthic foraminifera $\delta^{18}O$ isotopic record of deep water temperature, to reconstruct past NAO indices (Brutckner and Mackensen, 2006). While the authors conclude that no multidecadal variation in the NAO is evident from their dataset, particularly due to the rapid oscillations of the LIA pattern after 1600 A.D., the trend (see Figure 2.2) also shows the same signature as Proctor et al. (2000) for the thirteenth through sixteenth centuries, with a strong positive NAO index prevalent in the thirteenth century and a rapid decrease thereafter in the fourteenth century, remaining relatively low through to 1600. This corresponds to the Gothic period and appears to justify, based on winter cloud cover patterns associated with the NAO, an increasing awareness of cloud cover conditions in the fourteenth century as the NAO index decreased rapidly. This shift in NAO index, especially evident by the early fourteenth century, seems to have manifested itself during the Great European Famine, which plagued much of northwestern Europe with extreme conditions typical of low or rapidly fluctuating NAO patterns and a more southward-displaced jet (Fagan, 2000).

Another mechanism that may be useful in analyzing long-term NAO variability is the sea ice extent near Iceland. Mysak and Venegas (1998) confirmed that increased sea ice coverage in the Barents Sea corresponded, on annual time scales, with substantial decreases in the NAO index. The physical mechanism for this trend is well-regarded; greater sea ice coverage cuts off latent heat fluxes from the ocean to the Icelandic Low, increasing surface pressure near Iceland and forcing the Icelandic Low southward and/or weakening it.

Dawson et al. (2002) also illustrates this complex NAO-sea ice relationship and indicates that greater sea ice coverage likely leads to the southward-shift in the subpolar jet and increased storminess over Europe. Longer-term patterns in sea ice cycles, then, may help illustrate the persistency of the NAO sign on long time scales. For example, Ogilvie (1984)'s decadal sea ice index for Iceland extending back to 1600 does confirm a multidecadal peak in sea ice corresponding to the Late Maunder Minimum which Luterbacher et al. (2001b) and other

sources indicates was likely dominated by low NAO indices. Koch (1945) provided an index extended back to 800 A.D., but Ogilvie's more refined methods reveal that the data was likely too sparse to produce an comprehensive decadal sea-ice index extending back to the Middle Ages. However, she does document all relevant sources, which reveal a relatively calm climate during the tenth through twelfth centuries (with only two scattered reports of famine), followed by a series of years (starting in 1180-1212), for which severe weather and harsh ice conditions were recorded by chroniclers (Ogilvie, 1984). Reports of such incidents became more frequent, with extreme conditions reported in 1233, 1252, 1280s-1290s, 1320-1323, 1331, 1341, and 1350 (Ogilvie, 1984). By around 1364, Ivar Bardarsson (in Norway) made note that the old route to the Norse colonies had become treacherous due to large amounts of sea ice (Ogilvie, 1984). Extrapolating trends from these reports needs to be done with caution because of the lack of records from the earlier period. However, if taken at face value, the greater sea ice coverage documented around Iceland may have accompanied greater prevalence of the negative phase NAO events during the transition to the LIA.

New proxy methods, based on shallow water sediment cores of diatoms containing the chemical compound IP_{25} (which is more prevalent in diatoms associated with sea ice) presented in Belt et al. (2006) and Massé et al. (2008), provides a reconstruction of sea ice extent in Iceland and the location of polar fronts, and it generally agrees with interpretations by Ogilvie and data seen in the Baltic Sea and Scotland NAO proxies, with a significant increase in sea ice off the north coast of Iceland starting in 1300. In addition, in Iceland strong correlations between glacial extent and sea ice coverage have been documented, and further studies of Icelandic glaciers may reveal an NAO signal (Mackintosh et al., 2002). Glacial advances have been documented in Iceland since 1200 A.D., and this may provide a source for further investigation (Gudmunsson, 1997). Also, other NAO proxy records may eventually be developed from Alpine or Norwegian glaciers, whose mass balances have in the case of Nigaardsbreen (Norway) and Rhonegletsher (Switzerland) proven to significantly correlate and anti-correlate (respectively) with the NAO (Reichert et al., 2001; Reichert et al., 2002; Six et al., 2001). Historical glacial length fluctuations, which vary according to long-term climate and temperature trends, can be documented through proxy methods, and from these glacial mass balances can be simulated using a dynamical ice flow model (Reichert et al., 2002). Already it has been suggested by Nesje et al. (2003) that the rapid expansion of Norwegian glaciers during the MWP could not be

attributed to decreasing temperature alone and may be linked to a sustained positive NAO pattern. In general, however, using the NAO reconstructions already developed, it can be reasonably concluded that negative NAO index circulation patterns became more prevalent during the Little Ice Age compared to the twelfth and thirteenth centuries, and that a rapid regime shift may have occurred around 1300, or as suggested by the Iceland records, started even earlier.

Therefore, we propose that the Gothic era is suitable for analyzing architectural responses to likely increases in precipitation and cloud cover across continental northern Europe, especially given trends associated with the NAO and summer effective precipitation patterns. In addition, from the corroborating evidence provided by the various proxy indicators above, it is clear that the twelfth and thirteenth centuries in northwestern Europe were likely sunnier than subsequent centuries, with a rapid transition between the two climate regimes occurring over the course of the thirteenth century or fourteenth century. This shift, in turn, occurred during a period of remarkable architectural changes and adjustments, during which windows had become larger than ever before and were often glazed for the first time. Experimentation with glazing transmission (a newly important medium) in these structures started during the sunnier period and continued during deterioration of the climate in the thirteenth and fourteenth centuries. This likely shift in cloud cover climatology perhaps partly encouraged major northern Gothic churches and cathedrals to permanently adopt markedly more white glass in their programs, which is better suited for illumination under cloudy conditions. That is, changes in cloudiness might have encouraged the adoption of whiter glass and/or may have helped prevent a return to an earlier, low-transmissivity aesthetic. Therefore, this thesis will evaluate daylighting performance in early and late Gothic programs under both cloudy and sunny conditions to better define the climatic contribution to the relationship between stained glass and architecture.

Chapter 2 Tables and Figures

Table 2.1: Compilation of results from various peat bog studies, table adapted from Barber et al. (2004a), and dates are in years before present (B.P.). For the corresponding references, refer to Barber et al. (2004a) listed in the references at the end of this thesis.

Sites	References	Wet shift dates									
Abbeyknockmoy	Barber *et al.* (2003)		700	1050	1400	1750		2200	2750	3150	4000
Co. Galway, Ireland											4250
Mongan Bog	Barber *et al.* (2003)	450	600			1600		2250	2350	3200	
Co. Offaly			850			1800			2450		
Ireland									2750		
Kentra Moss	Ellis & Tallis (2000)	330	600	1150	1400			2150	2550	3250	
western Scotland			880								
Talla Moss, Borders,	Chambers *et al.* (1997)	540		1100		1700	1930	2270	2600	3460	
Scotland											
Temple Hill Moss,	Langdon *et al.* (2003)	250			1450				2800	3400	4500
southeast Scotland										3850	
Border Mires northern	Mauquoy & Barber	180	850	1030	1400	1740	1980	2130	2540		
England	(1999a, b)	550							2710		
Bolton Fell Moss,	Barber (1981), Barber *et al.*	210	620	1000	1400			2200	2350	3020	4020
Cumbria, England	(1994), Barber *et al.*	500	720						2440	3200	4280
	(2003)								2580	3600	4420
									2900	3750	4620
Walton Moss	Hughes *et al.* (2000)	100			1450	1750			2320-2040	3170-2860	4410-3990
Cumbria, England		350								3500	
South Cumbrian bogs,	Wimble (1986)		600	1050	1350	1700		2250	2900	3400	4300
England			800		1500			2250		3500	
										3800	
British and Irish blanket	Blackford & Chambers	490		1150	1310		1910				
bogs	(1991, 1995)				1330						
Engbertsdijksveen	Van Geel (1978), van Geel								2850	3020	4350
The Netherlands	*et al.* (1996)								2750-2450	3750	
Bourtangerveen	Dupont (1986)						1950			3650-3300	4450
The Netherlands											
Draved Mose	Aaby (1976)	450	660		1500	1700		2250		3000	4000
Jutland, Denmark			860							3400	4300
											4600
Dosenmoor	This paper		600		1400		1950		2750-2600	3350	
Svanemose	This paper		700	1080	1350	1800	1950		2650	3500	

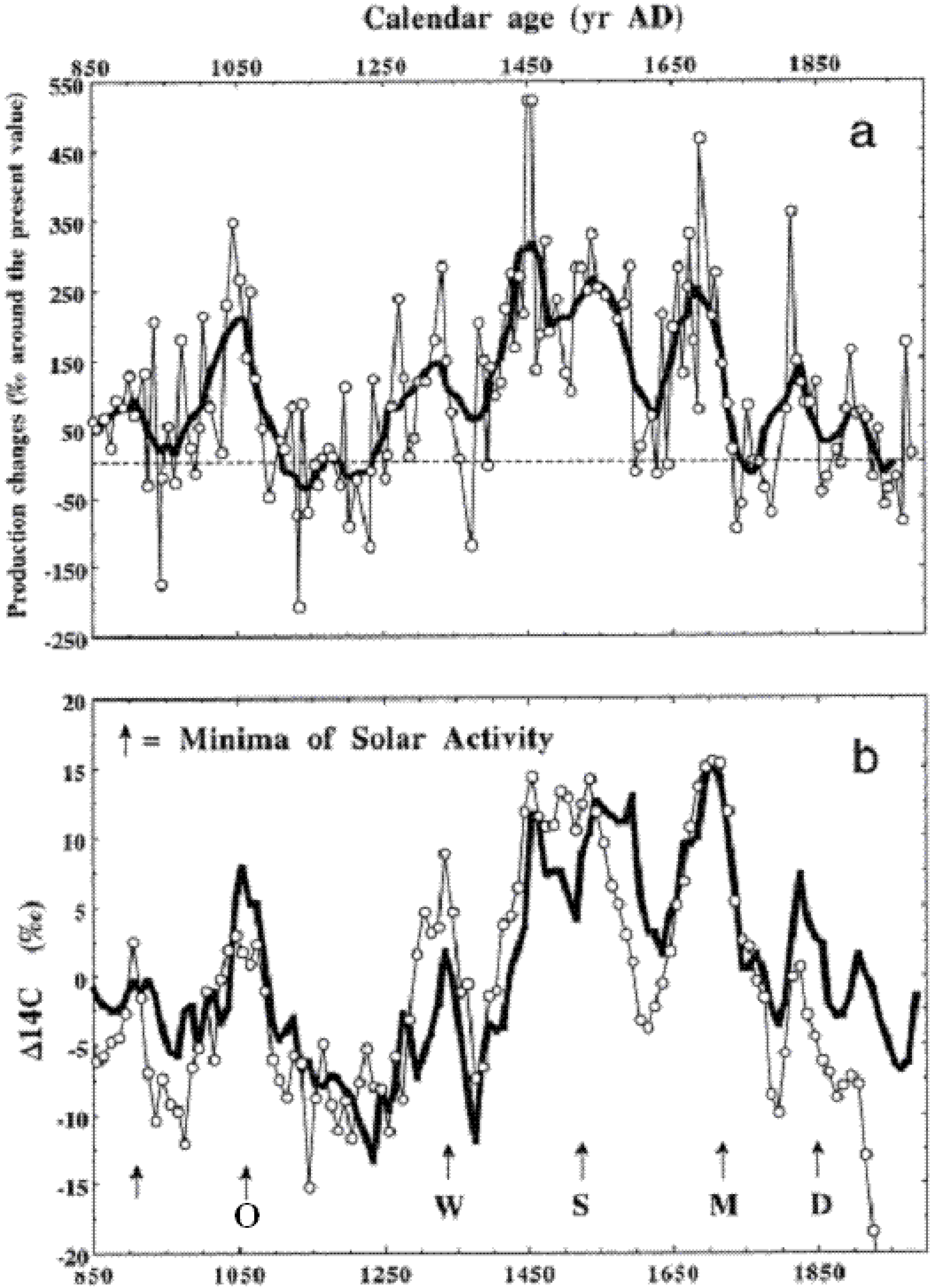


Figure 2.1: Isotope record for (a) Galactic Cosmic Ray flux from Raisbeck et al. (1990) with open circles showing original data and the solid black line representing a smoothed curve using a Gaussian filter, and (b) solar activity as measured in $\delta^{14}C$ from tree ring records (open circles) from Stuiver et al. (1980) and computed from a 12 box model (solid line); adapted from Bard et al. (2000).

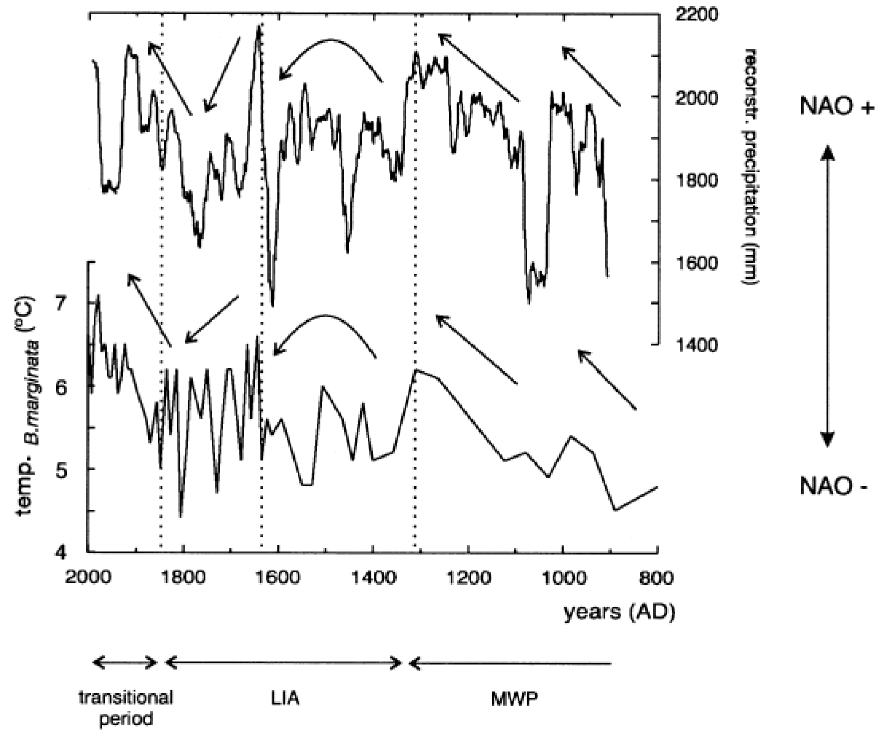


Figure 2.2: Proctor et al. (2000)'s precipitation index for Scotland (top) aligned with Brutckner and Mackensen (2006) NAO proxy record (bottom); adapted from Brutckner and Mackensen (2006).

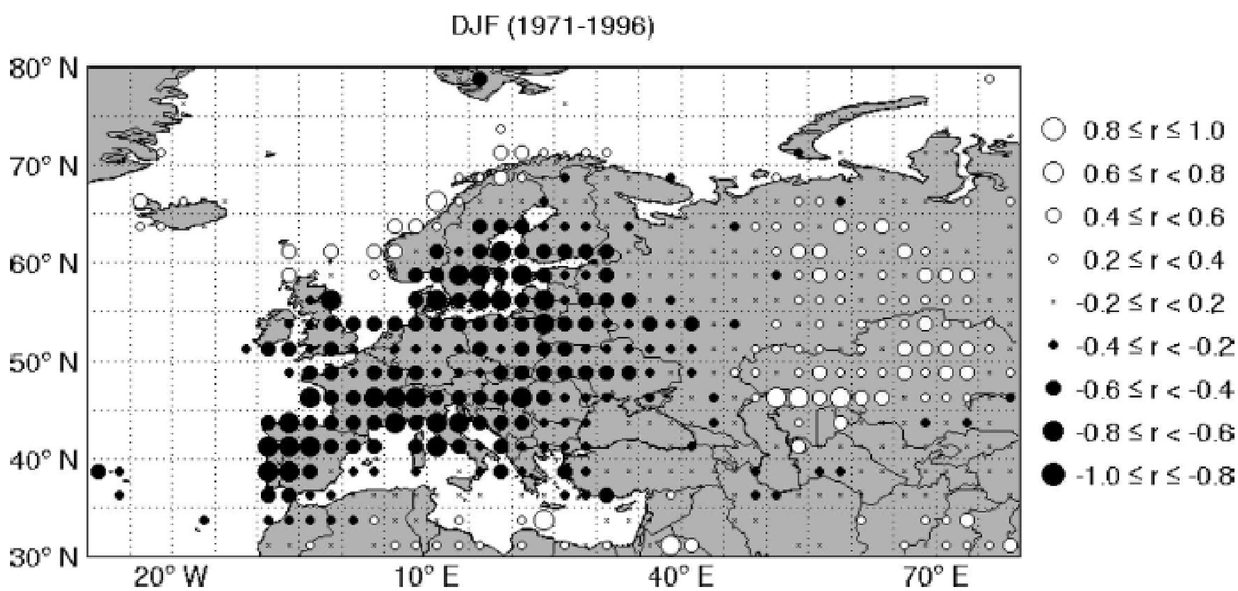
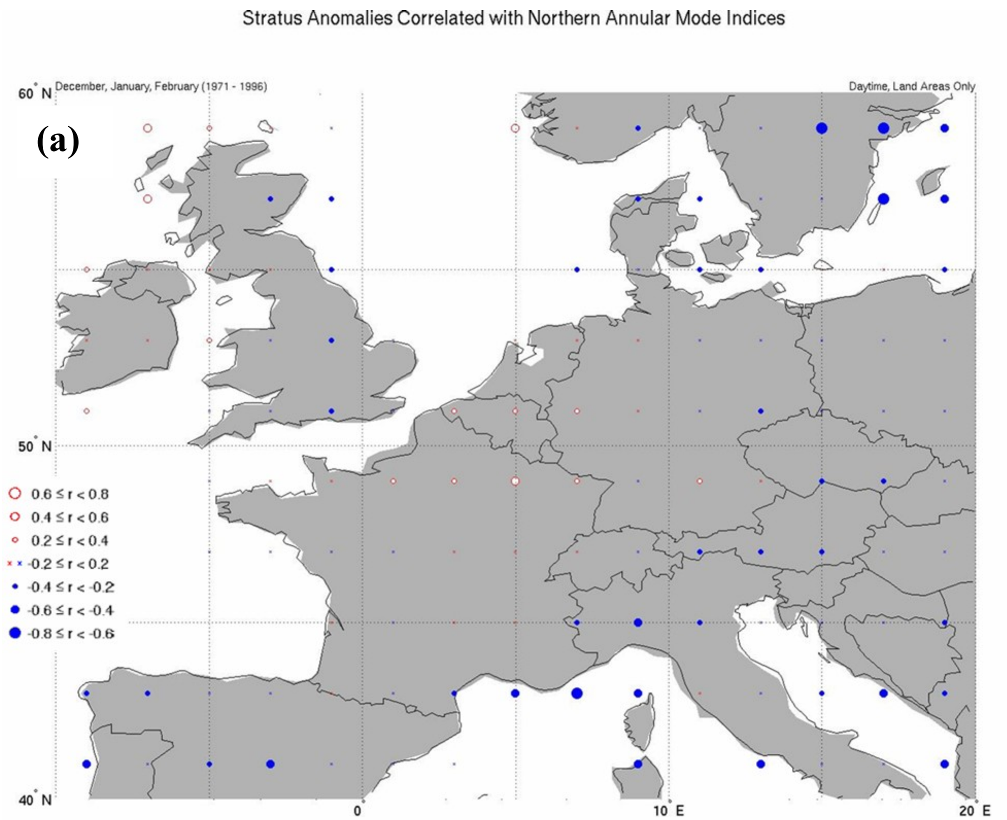
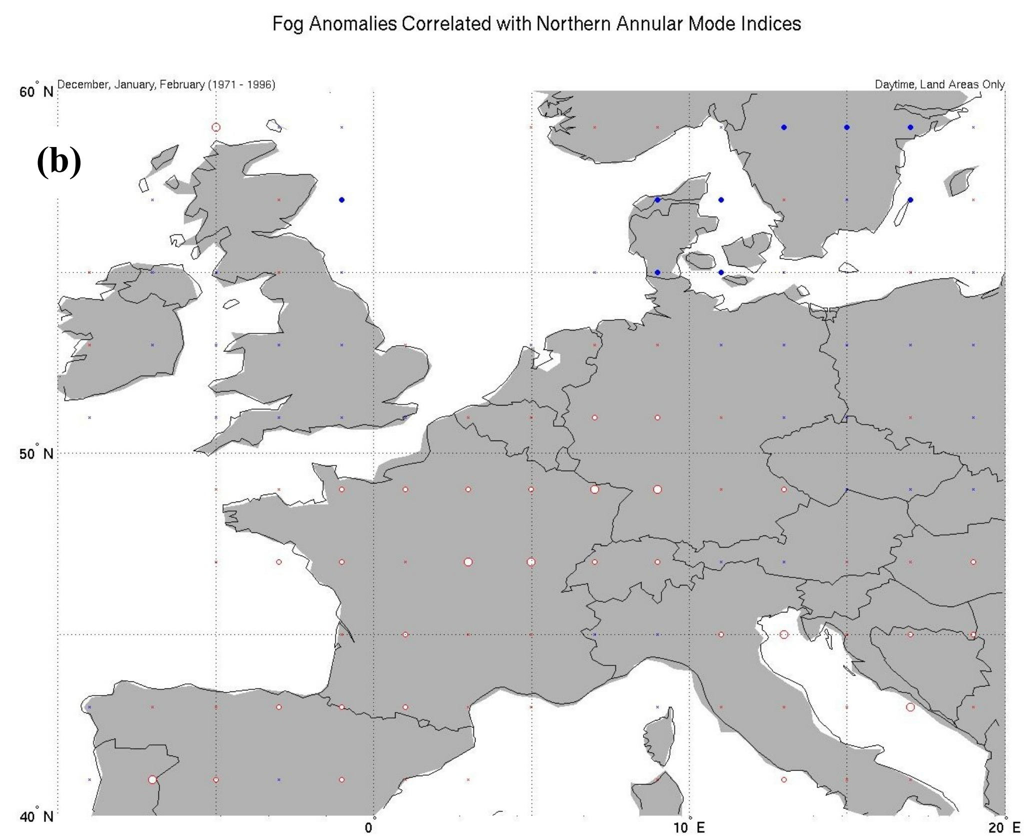


Figure 2.3: Nimbostratus anomaly correlations with the Northern Annual Mode (related to the NAO); adapted from Warren et al. (2007).


Stratus Anomalies Correlated with Northern Annular Mode Indices
December, January, February (1971 - 1996)
Daytime, Land Areas Only
(a)
60° N
50° N
40° N
0
10 E
20 E
0.6 ≤ r < 0.8
0.4 ≤ r < 0.6
0.2 ≤ r < 0.4
-0.2 ≤ r < 0.2
-0.4 ≤ r < -0.2
-0.6 ≤ r < -0.4
-0.8 ≤ r < -0.6


Fog Anomalies Correlated with Northern Annular Mode Indices
December, January, February (1971 - 1996)
Daytime, Land Areas Only
(b)
60° N
50° N
40° N
0
10 E
20 E

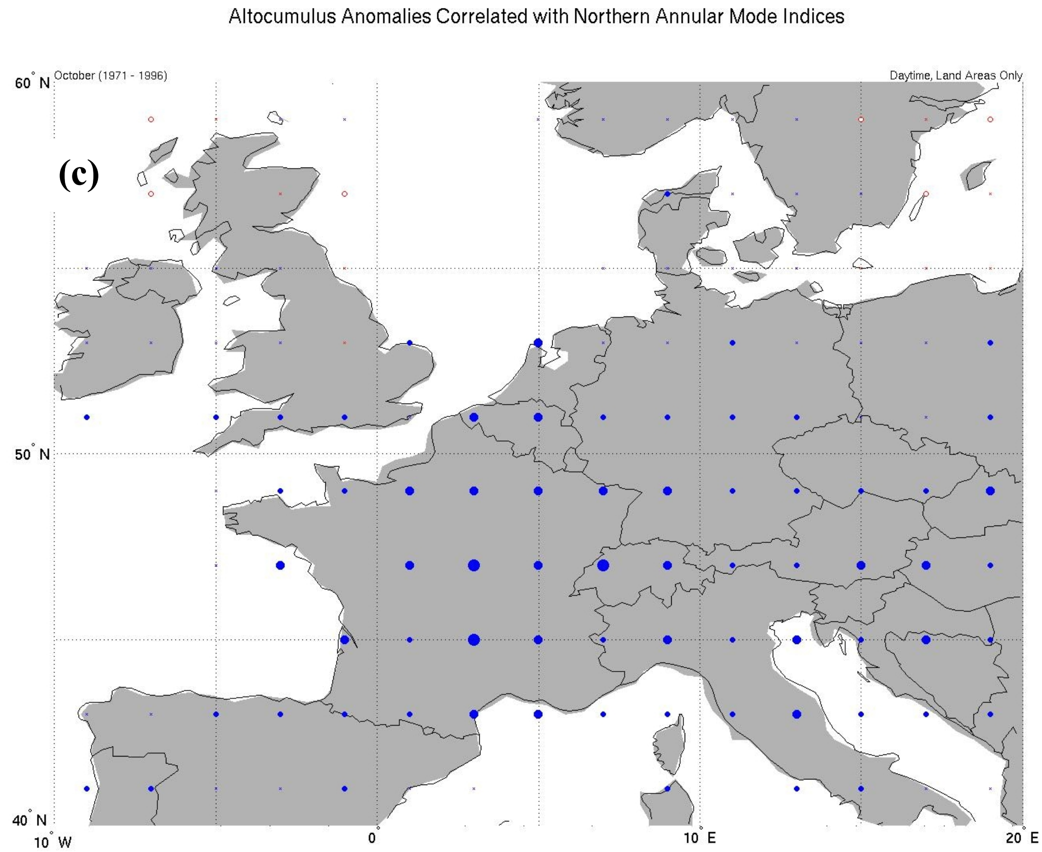


Figure 2.4: Anomaly correlations with the Northern Annual Mode (related to the NAO), with correlation coefficient legend in (a). Correlations provided for (a) stratus, (b) fog, and (c) Altocumulus. Adaptations of original images provided courtesy of Stephen Warren and Ryan Eastman, University of Washington (Personal Communication, 2007).

3 Data and Methodology

3.1 Site Selection

The evidence presented above for trends in medieval cloudiness suggests that increasing cloud cover in Northern Europe may have indeed been a concern for interior lighting aesthetic, especially given that northern Gothic cathedrals are widely perceived to have prioritized daylighting over other means of architectural expression (Janson, 2001; Wachs, 1964). Given the constraints in time and funding for this project, we decided to focus on cathedrals and churches in Northern France and southwestern Germany. A sampling of Mediterranean church interior lighting was also obtained through an analysis of Spanish cathedrals. English glazing is discussed qualitatively and more extensively in Simmons (2007) but are not addressed in this thesis. Given the high prevalence of large windows glazed with grisailles during the early Gothic era, it would not be surprising that most English cathedrals tried to maximize interior lighting for a cloudier climate from the outset. This corroborates with data presented by Meerkötter et al. (2004) and Fontoynont (2002), which demonstrate a broadly cloudy climatology for much of the British Isles. Even during the likely positive NAO phase winters of the MWP, the British Isles lie relatively close to the mean storm track identified in Section 2.3 on NAO trends, implying that much cloudier conditions may have been prevalent during English winters compared to the continent. These climatic indicators, in turn, may have helped motivate an interior lighting design suitable for both cloudy and sunny weather (and nowhere is this more evident than in the bright, heavily-grisailled interior of York in northern England).

While English cathedrals represent relative constancy with time (employing whiter glass and/or greater translucency glazing), French cathedrals on the other hand demonstrate a mixture of traditions and thus provide the best opportunity to measure interior lighting under both full-colour and grisaille-dominated stained glass programs. In addition, French cathedrals retain more of their original stained glass than many other parts of Europe (and particularly with regard to England, where much was destroyed during and after the Protestant Reformation). Also, the best original glazing programs in France are constrained to a relatively small region around Paris (Picardie, Normandie, Sarthe, Loire, and Champagne). Because lighting studies require close control on the quality of exterior illuminance (sunny vs. cloudy conditions), a successful operation depends largely on the weather, and due to their close proximity to each other French cathedrals also allow the best versatility in terms of choosing the appropriate weather conditions

to collect data (most operations were made as day trips from Paris as a result). Major Spanish cathedrals, on the other hand, are widely spread apart, and to minimize expense we had to accept whatever weather conditions we encountered; thus, the overview from Spanish cathedrals is limited in scope. By contrast, French cathedrals, for which data have been collected strategically in various interiors for both sunny and cloudy conditions, are the primary focus of this thesis. These structures also represent the best region for experiencing the significant climate transition during the thirteenth and fourteenth Centuries, and they cover a region where the climatological latitudinal cloud cover gradient has shown to be greatest, according to modern data (Meerkötter et al., 2004). Thus, even small shifts in the cloud cover gradient may bring relatively large changes to the cloud climatology and cloud variability in this region, making cathedrals between northern France to the Loire valley potentially more sensitive to climate forcing. Two separate data collection operations were performed, one in the spring (April to June) of 2007 and another in the winter (December and January) 2007-2008, and several churches were analyzed under both winter and summer illumination conditions to document seasonal illumination variability.

3.2 Cathedral Interior Illuminance Analysis Methods

In order to collect luminance data, we employed four Extech 407026 illuminance meters (technical considerations regarding our individual instruments are discussed in Appendix II). Our method of data collection was proposed to us by a special session of lighting experts at the National Research Council of Canada led by Dr. Jennifer Veitch. Rather than focusing on light received by specific windows, they suggested that we instead thoroughly document the ambient illuminance at regular grid points in various interiors, even with contamination from modern windows, to obtain a range of possible lighting conditions that represent a particular era. We followed their suggestions, using the natural coordinate system (vault intersections) provided by medieval architects as the focus of our gridded measurements. Vault boss locations are often fully exposed to direct lighting from side aisle windows and thus sometimes provide areas of maximum possible illumination in the church. In most cathedrals measurements were only taken underneath vault intersections given limited time, but for comparison in some churches, such as Chartres and León, illuminance measurement series were taken at points between columns (in addition to under vault intersections) to demonstrate any differences.

In general, lighting from clerestories and tall aisle-level windows provide maximum diffusion of daylighting so that there were few to no detectable differences between the vault

intersections and the vault bosses in most cases. We analyzed as many regions of the church as possible, i.e., those that were readily accessible to us and were in reasonable proximity to original stained glass. This makes possible a direct inter-church comparison between lighting conditions in specialized areas of the church and allows, for example, the comparison of nave lighting in different churches (C. Reinhart, personal communication, 2007). Fewer choir measurements were obtained during the study, although we were able to take them in Tours, Cologne, Angers, Le Mans, and St-Etienne-du-Mont (Paris). Specialized conditions (such as scaffolding, blackened windows, and other obstructions) were present in some locations and affect some data points more than others, and these are noted either in the database or in the supplementary materials provided online. The greatest contaminations are likely associated with light admitted by modern or anachronistic windows and the inter-reflections associated with these apertures. While more modern exterior obstructions on the outside are also a concern, most of the churches and cathedrals analyzed were surrounded by one or more open squares, which were further surrounded by low-rise historical buildings that often replicate (or do not represent a strong divergence from) the original obstructions during the Middle Ages. Therefore, in most cases exterior obstructions were not considered important factors in the modification of the original daylighting aesthetic.

In the majority of cathedrals and churches, measurements were taken in a variety of different directions at each point, unless time or lighting restrictions encouraged limiting the number of measurements obtained. In all cases the horizontal illuminance measurement was taken first at a noted time, and then vertical directional measurements (east, west, north, and south at the height of the tripod or observer) were taken; these latter directions pertain in each case to the axial direction of the church or cathedral (more relevant to an observer in the church rather than the actual cardinal directions). The axial orientation of cathedrals are defined as follows: when standing at the west front (main portal entry) and facing the choir/altar, east is always in the direction of the choir/altar, south is 90° to the right of this direction, north is 90° to the left of this direction, and west is 180° from this direction. Following the same four vertical measurements, often a series of 45° directional illuminance measurements were taken, either toward specific windows or in all four directions to determine any preferred directionality associated with the horizontal measurements (such as direct lighting contributions from specific clerestories with respect to the measurement point). In addition, most interior lighting

illuminance measurements were taken at a standard tripod height of 125 cm. However, in some instances, such as at León and Sevilla, measurements were taken at the height of the observer (170-175 cm). A variety of tests were performed in the cathedrals between observation elevations, and it was observed that, given the low transmissivity of the windows and the deep diffusion of light throughout the interior, the illuminance at tripod height and observer height were almost always the same. Thus, while height of measurements are thoroughly recorded in our database, for the purposes of this study the illuminances at the slightly different heights were considered to be the same, both essentially representing the approximate height of a human observer during the medieval period (see Schweich and Knusel, 2003).

Because the objective of this thesis is to document natural daylighting in sacred interiors, the artificial lighting used in many cathedrals today was of particular concern. Wherever possible, we arranged for artificial lighting to be turned off in the interior in order to return it to its original lighting state. If this was not feasible, we would redo all of our measurements at night using the same instrument as during the day and later subtract the nighttime measurements from the daytime measurements (as suggested by the special session at the NRCC) while keeping the artificial lighting exactly the same as it had been during the daytime measurements. In some cases we were not granted access (Segovia, Sevilla) past a certain hour before sunset, which forced us to do a partial analysis or concede that artificial lighting would be a permanent part of our measurements. In most cases, however, we were able to take nighttime measurements and subtract them out to give us a daylight-only illuminance profile of the various analyzed cathedrals. It was of some concern that the artificial lighting outside the cathedrals coming from the surrounding city or the cathedral façade lighting could also be a factor in the nighttime measurements. However, in León and Cologne several measurements were taken near windows receiving a substantial amount of artificial exterior lighting (but low interior artificial lighting), and even our most sensitive instruments yielded 0 lux in these locations. Therefore, the artificial lighting coming from outside the cathedral was deemed negligible for our particular illuminance meters, but they are a factor in any nighttime luminance profiles of artificial lighting in the interior.

3.3 Exterior Illuminance Analysis Methods

3.3.1 Procedures and Daylight Factor Calculations

Lighting analyses were conducted primarily under two different types of weather conditions—largely sunny, clear sky regimes and under completely overcast skies (with only a few cases done under partly cloudy skies). This was done to simplify the sky luminance profile such that assumptions based on the Commission Internationale d'Éclairage (CIE) standard luminance distributions could be readily applied to the dataset. During clear sky conditions, because of the slowly changing position of the solar disk in the sky, measurements could be taken at longer intervals (for example, every 30 minutes or so) without the aid of a volunteer assistant on the exterior, and for these situations luminance at every position in the sky can be easily estimated using CIE models (Kittler et al., 1997). Correspondingly, from these distributions, using methods such as those provided in Moeck and Anaokar (2006) and Betman (2005), illuminance for a given field of view can be estimated with a high degree of accuracy. Regular exterior measurements, however, are most vital under the cloudy sky regime, where cloud cover undulations and changes could produce relatively fast variations in exterior illuminance; thus, a volunteer assistant took measurements on the exterior at regular intervals (usually every two to three minutes) at the same time measurements were taken in the interior of a church or cathedral. Often only exterior horizontal illuminance measurements were made, but when possible measurements were also taken in the four axial direction of the church, at both vertical (90° with respect to horizontal measurements) and 45° directions. These supplementary data can also be useful in determining whether the CIE standard overcast sky (with virtually equal illuminance contributions from all directions) or another luminance distribution model is most appropriate.

Overcast skies allow the calculation of both horizontal (Robbins, 1986) and vertical (Cheung and Chung, 2005) daylight factors. Both daylight factors are particularly stable under the CIE standard overcast sky luminance distribution, where incoming illuminances are roughly equal in all directions at any given moment. For our purposes, we define (Eq. 3.1) the horizontal daylight factor (HDF) as described in Betman (2005):

$$\text{HDF} = (E_{d,i,h}/E_{d,h}) \cdot 100\% \qquad (3.1)$$

$$\text{VDF} = (E_{d,i,v}/E_{d,h}) \cdot 100\% \qquad (3.2)$$

Where $E_{d,i,h}$ is the interior horizontal diffuse illumination (the only illumination available under completely overcast skies is diffuse) and $E_{d,h}$ is the unobstructed (hemispherical sky-view) measure of the exterior horizontal diffuse illuminance (again, under overcast skies the total

exterior illuminance is entirely diffuse). Correspondingly, the vertical daylight factor (VDF, in Eq. 3.2) is defined in the same way, except that $E_{d,i,h}$ becomes the vertical interior diffuse illuminance $E_{d,i,v}$ in a given direction (Cheung and Chung, 2005). Both vertical and horizontal daylight factors should be constant under any uniformly overcast sky, so that regardless of the season or thickness of the cloud, given any exterior horizontal illuminance value the corresponding interior illuminances can be determined if the daylight factors are known. This provides a particularly useful method for comparing different interiors using the same standard and is applied rigorously in our analyses.

Between each time step the exterior illuminance was assumed to increase or decrease at a linear rate, and the corresponding value of the interior measurement was divided by the exterior value taken in the same minute (or a linear rate-derived estimation between the two nearest measurements). It should be noted that time pieces were synchronized; however, the precise second of all measurements were not recorded and all times are thus known within one minute (but when seconds were recorded, such as during the second round of DF measurements in Chartres, the times are considered accurate to within 10 seconds). In some locations daylight factor measurements were repeated, and in such cases they were averaged together for a more accurate measurement. When this was done, such as at Tours and St-Serevin, the two daylight factors evaluated were often very precise, thus allowing for confidence in interiors where daylight factor measurements were not repeated. When simultaneous interior and exterior measurements were not possible (i.e., there were more than five minutes between exterior measurements), the term ‘estimated daylight factor’ is used in the results. In these cases the observer waited for a relatively stable cloudiness condition (either steadily increasing or decreasing horizontal illuminance or nearly constant horizontal illuminance between the two measurements) to perform the measurements so that exterior horizontal illuminances could be better estimated in the interim.

For daylight factor evaluation, the most common application involves placing an illuminance sensor on the roof of the building and assuming a hemispherical sky view. However, for our purposes this methodology was deemed inappropriate given the frequent presence of tall towers and spires surrounding the roofs of most medieval churches and cathedrals (which afford significant obstructions to the sky view). Therefore, following the recommendations of Dr. Christoph Reinhart (Lighting Analyst, formerly at NRCC and now at Harvard University), we

chose instead to do our exterior lighting analyses at particularly open locations or rooftops near the church or cathedral being analyzed. Individual locations are thoroughly documented as part of our databases and supplementary online material. Because our outside observer was always a volunteer, every effort was made to assure their comfort, sometimes at the expense of an entirely hemispherical sky view. In a few cases perfect or nearly perfect hemispherical views were achieved with only distant, minor, or no exterior obstructions; such examples include the overcast sky analyses of Chartres, Cologne, Strasbourg, Tours (cloudy weather analysis), and Troyes. In most other cases the exterior views were deemed equivalent to unobstructed in the horizontal measurements (Bourges, Évreux, Segovia, and Rouen), even if a minor obstruction was present nearby (such as a few trees or a low, two or three story building at a distance of 30 meters or more).

3.3.2 Validation Experiments

If the hemispherical nature of the exterior sky view was regarded as potentially circumspect due to the presence of an obstruction, validation experiments were performed (when possible) to prove otherwise or make corrections as needed. In these cases the methods of exterior daylight factor analyses, such as demonstrated in Cheung and Chung (2005), were deemed appropriate. In this case, exterior (rather than interior) vertical or horizontal daylight factors were calculated according to Eq. 3.1 above, where $E_{d,i,h}$ instead represents the vertical or horizontal illuminance in an exterior location with obstructions and E_d remains the exterior horizontal diffuse illuminance in a location with an acceptably quasi-hemispherical sky view appropriate for traditional daylight factor calculations. For example, in Paris most of our exterior measurements were taken in the Jardins du Luxembourg. Thus, to verify the appropriateness of this location we performed simultaneous measurements in the Jardin du Luxembourg and on the helicopter launch pad on the publicly-accessible roof of the Tour Montparnasse (with an unobstructed exterior sky). No perceivable underestimation of the horizontal exterior illuminance in the Jardins du Luxembourg due to the surrounding obstructions was detected, thus deeming the Jardins du Luxembourg skyview as quasi-hemispherical and adequate for daylight factor calculation. Other similar verifications between obstructed and unobstructed skyview locations were also performed in Angers, Bourges, Paris (Pont d'Arcole), and Tours.

Even for the most heavily obstructed exterior locations, such as at Tours and Angers where the west front towers block a significant portion of the sky, exterior daylight factors were

still close to 90%. Furthermore, the first round of daylight factors in Évreux were taken in the Place Charles de Gaulle, and despite the presence of low-rise buildings along the periphery of the square horizontal measurements from this site corresponded nearly exactly to those in a location with a hemispherical sky view. This would allow us to assume that comparatively open locations such as at Bourges, Troyes, and Rouen likely have higher exterior daylight factors, thus allowing us to consider them quasi-hemispherical and suitable for daylight factor calculation. In the validation experiments, the lack of leaves on trees in other parts of the Jardins du Luxembourg during the winter validation experiment were not deemed an issue due to their distance from the measurement site. However, tree leaves would likely be an issue for a future validation experiment in Rouen for the St-Ouen dataset. In addition, it should be noted that sunny skies do not validate in the same manner as cloudy skies. With the elevated solar angle during the summer measurements, any horizontal measurement taken in a reasonably open location was expected to be dominated by the high luminance provided by the solar disk, and winter validations for slightly obstructed and unobstructed locations (Bourges) revealed similar values such that greater leverage with regard to location skyview could generally be applied when taking exterior measurements under sunny conditions.

3.3.3. HDF and VDF-Based Horizontal Illuminance Prediction Algorithm

In a few cases, such as the Angers daylight factor analysis, only a limited amount of data is available from the exterior due to the availability of only one observer. In this case, the observer took a series of interior measurements followed by an exterior measurement in an obstructed location nearly 20 minutes later at a time when total exterior illuminance was decreasing due to a declining sun. Even if we were to assume a uniform overcast cloud cover unchanging in thickness, drop concentration and optical depth, the first interior measurements would not likely reflect the exterior measurement due to the background decreasing illuminance. However, a 20-minute series of east-facing measurements were available following this exterior measurement, and a validation experiment (with horizontal and vertical illuminances) was later performed between the obstructed site and a bridge with a largely unobstructed view. The average east-facing VDF between the obstructed site and bridge could thus be calculated. The illuminance decrease in the east-facing direction, assuming an average CIE standard overcast sky distribution, could also be assumed to be directly proportional (through the average east-facing VDF) to the decreasing trend in total exterior illuminance. The decreasing trend in

horizontal or vertical illuminance on an overcast day would likely follow a sigmoid function, but in the afternoon for a short time period (less than one hour) a linear decreasing (least-squares regression) trend was deemed an adequate representation of the background illumination decay. Using this trend line the unobstructed exterior horizontal illuminances at the times of interior measurements were hindcasted. This was done using two different methods (the second time using an HDF relationship between the two sites) and they were averaged together. Using the same methods in Tours (which also saw an even cloud cover during operations and for which the actual illuminance values in the two exterior locations are known) on the same twenty-minute interval yielded a prediction that was within 7% of the actual measured value.

3.4 Interior Luminance Analysis Methods

An extensive interior luminance analysis also complements any detailed architectural lighting study. Luminance surveys may be particularly important in cathedrals, as bright spots associated with windows and nearby walls of cathedrals may serve as visual focal points as well as a means of illuminating the architectural aesthetic of the building (this is particularly the case with the choir hemicycle, a focal point of light within a church). In many cases, the bright areas of visual interest are the windows themselves, and these may have been particularly important features in Romanesque and Early Gothic churches with partial full-colour programs such as Le Mans and Strasbourg, where interior illumination might have originally been very low. In addition, illuminance meters do receive light from such bright spots, but because illuminance measures ambient lighting and behaves according to the inverse square law, the values provided by an illuminance meter might underestimate the importance of bright visual focal points located higher up or at a distance from the illuminance sensor. For example, an observer standing at the west front of a cathedral may concentrate on the bright choir hemicycle, which is visually aligned (in French churches) with the nave; however, an illuminance analysis adjacent to the west front is unlikely to detect the direct light visible from such a distance away. Thus, for an observer the actual ambient illuminance at points in the nave may be less visually relevant than the luminance of areas further away). Therefore, luminance performance during cloudy and sunny conditions for different types of stained glass programs also needs to be evaluated in order to obtain a more comprehensive view of the interplay of ambient lighting and visual focal points within a cathedral interior.

Unfortunately, due to the expense of exterior luminance scan instruments and interior point luminance meters, we were unable to perform as comprehensive and verifiable luminance analysis as might otherwise be possible. However, we were able to use a Canon Digital Rebel XTi 10.1 MP SLR camera, a model recommended to us by Pierre-Félix Breton (architectural lighting/modelling analyst), to create High Dynamic Range (HDR) images and associated luminance maps. In order to take the photo series used to create the HDR images, we approximately doubled the exposure time step between each individual photo from 1/4000 s to 30 s, as discussed in Moeck and Anaokar (2006) and Beltrán and Mogo (2005), while keeping the f-stop, ISO, and white balance constant in the manual adjustment mode of the camera. We most often used the settings of ISO 100, f-stop 4.0, and daylight white balance, which were recommended to us by Dugyu Cetegen, HDR luminance specialist at the NRCC. However, during very low lighting situations we sometimes adjusted these settings, and these are thoroughly documented in our database. In addition, at night, when evaluating (when possible) the luminance contribution of interior lighting, we used the tungsten white balance setting (as many church officials and maintenance personnel were unable to confirm the lamp type or colour temperature used in the artificial lighting, although most appeared to have a cooler colour temperature and warmer yellowish glow). Most images were taken with the minimum focal length admitted by the lens (28 mm), and when higher focal lengths were used they were recorded. To avoid jiggle error and ensure that each pixel always represents the same point for each photo series, we controlled the camera settings and took the images remotely using EOS Utility software on a computer connected to the camera through a USB cable. We tried to take the photo series under either a stable cloudy or mostly clear sky conditions in most cases so that the lighting was less dynamic (so that no major changes in exterior illumination occurred as the photo series was being completed) and exterior luminance distributions could be solidly estimated using CIE sky standards. In addition, we documented exterior and interior illuminances, angle, height, and locations for most photo series when possible. Exterior illuminances were often evaluated outside the window of interest or from a similar viewpoint as the window during or immediately after the photo series at the same angle of inclination at which the photos were taken. More data were collected when feasible, such as the vertical or horizontal illuminances on the outside near the time that the photo series was taken.

The images were later assembled into Photosphere © (www.anyhere.com) designed by Greg Ward. The dynamic range of each HDR image was verified through an analysis of RGB values of the brightest and darkest incorporated photo according to the settings recommended by Reinhard et al. (2005) to obtain the most accurate camera response curve and luminance values. The luminance calculation methodology and algorithms are thoroughly discussed by Inanici (2006) and Moeck and Anaokar (2006). Both studies also indicate that one of the most important sources for luminance error derive from vignetting (or light fall off) that occurs when moving away from the centre of the lens. To reduce light fall off, a bayonet-type lens hood was placed on the lens during all measurements. In addition, to avoid vignetting we chose only to rigorously evaluate luminances associated with pixels near the centre of each image, although vignetting errors can easily be corrected through experimentation and will be done in future work.

Many of the HDR images assembled focus on individual windows rather than on the broader interior lighting regime. The luminance values for individual panes also provide a relative measure of glazing transmission. For example, adjacent red and white medieval panes that were well-preserved likely receive similar illumination on the outside, and therefore, differences between their interior luminance value speak to their transmission abilities with respect to each other. Because of the high resolution capacity of the camera used, each glass pane can often be represented by a field of pixels that are averaged, and the originality of the individual panes can often be confirmed through the Corpus Vitrearum Medii Aevi series. The relative transmissions evaluated in this study are particularly useful when both Renaissance and medieval, medieval and modern, or Renaissance and modern panes are photographed within the same image (this is the case with many of our window photo series, most notably at Rouen Cathedral). Medieval stained glass also has a different purity with regard to Renaissance and modern glass, and HDR imagery thus has the potential to provide a scientific, quantitative method of analyzing and documenting restoration work done on the windows (provided that most ancient and modern panes are unblackened and in relatively good repair).

In the summer of 2008, photo series were also taken of a square diffuse reflectance standard (Gigahertz Optiks, Model OMD98-MP01, see http://www.gigahertz-optik.de/pdf/catalogue/Diffuse_Reflectors.pdf for more information) positioned against surfaces in church and cathedral interiors to measure their reflectances. Readily-accessible locations were

chosen, usually columns with colours considered representative of the typical stonework of the establishment being analyzed. The uncalibrated plate has a very stable average reflectance of 98% across the visible spectrum, and the luminance proportion between the reflectance plate and the directly-adjacent cathedral stonework was used to calculate the reflectance of the building material (J. Veitch, Personal Communication, 2008). For each individual HDR image, 10 luminance samples of the stonework surrounding the reflectance standard were taken and averaged to calculate an estimate of the reflectance for that particular sample. We obtained relatively consistent results in all cases, with most cathedral limestone possessing a reflectance in the range 45-55%. This allows a direct comparison between the data acquired in most interiors without regard to the effects of the stonework reflectance on the illuminance and luminance patterns, although in cases of extreme blackening (Chartres) this may not necessarily be the case.

4 Results

The results from this study focus on the daylight performance of glazed Gothic churches and cathedrals containing original glass from the late twelfth century to the sixteenth century. Because there are only a few particularly well-preserved programs from any one period in the evolution of stained glass, the results are presented chronologically as a collection of case studies that demonstrate a range in possible interior lighting values for each style of architecture and glazing. Daylight factor results are presented in cathedral plans in thousandths of a percent; however, the last significant digit is in the hundredths place. Due to instrumental errors and different states of preservation and maintenance of the original glazing, the actual numerical value of daylight factors and illuminance/luminance measurements in any one location is not always representative of the original illumination of the cathedral. However, the range of the values seen in a particular type of interior over many points lit predominately by ancient glass provides a good signal of the original lighting. This level of interpretation is thus the focus of the sections provided below. In addition, each cathedral case study concentrates on the lighting in a particularly well-preserved section of the interior space. For example, to best represent interior lighting conditions under thirteenth century full-colour/mixed programs, Chartres and Strasbourg are analyzed for their naves and side aisles, Bourges for its outer ambulatory, and Le Mans and Tours for their choirs.

4.1 Coloured Programs of the Thirteenth Century

4.1.1 Chartres Nave: An Expression of Thirteenth Century Architectural Lighting

Chartres perhaps provides one of the best expressions of the early, predominately richly coloured aesthetic of all of the sacred interiors we analyzed in France. Not only does Chartres retain more original glass than any other cathedral, but as a prominent pilgrimage destination, centre of mysticism, and focus of zeal surrounding the miraculous survival of the Virgin's Veil in the fire of 1194, it received ample patronage (allowing it to be essentially completed over the course of a few decades) to realize the full potential for the aesthetic design of its era. Its glazing program is thus largely of one period (the full-colour/mixed period of late twelfth and early thirteenth century glazing) in the evolution of Gothic architecture. Moreover, window placement and exterior obstructions are relatively similar to their original state during the Middle Ages. The cathedral's interior glazing has remained relatively unmodified over the centuries, except in the ambulatory where several grisailles were likely replacements from the second half of the

thirteenth century, the fourteenth century, and the sixteenth century (Lillich, 1972 , Grodecki et al., 1981). The original ambulatory was probably nearly completely glazed in full-colour windows (except for one mid-thirteenth century grisaille), similar to that of Bourges and St-Denis, according to Lillich (1972) and Grodecki et al. (1981). Therefore, we discuss lighting in the ambulatory of Chartres Cathedral within the context of trends during the grisaille revolution and the subsequent evolution of Rayonnant window glazing. Some of the original, likely coloured, choir clerestory windows are also missing, removed in the late eighteenth century to provide more light to the altar, and are now glazed with modern grisailles (Grodecki et al., 1981). On the other hand, the nave, which (except for the Vendôme chapel) is decorated entirely with its original windows, was analyzed from the perspective of its complete full-colour program. Both partly cloudy (summer) and cloudy (winter) measurements were performed in the nave to determine the character of lighting in the interior.

Several important features in the nave should be noted before interpreting these results. First of all, during the time of our operations in the cathedral the vast majority of clerestory windows were heavily blackened by corrosion (Figure 4.1). However, the aisle-level windows are in excellent repair (M. Lillich, personal communication, 2008). Another important concern (which is not as much of an issue for our other case studies) is the somewhat blackened state of the interior stonework, which serves to reduce internal reflections. A reflectance survey for several locations in the nave and transepts indicates that exposed raw limestone in the interior has a reflectance of 47%, probably more indicative of its original state during the Middle Ages. However, the typical darkened surface of today's interior has a reflectance of 24%, just over half of the reflectance of the original limestone, and similarly a luminance comparison between chipped (exposed) limestone and adjacent blackened stone for photo series of the nave vaults and south ambulatory (20 additional samples) revealed that the darkened stone was only 49% of the reflectance of the original limestone. Thus, the internal reflections in today's interior can be expected to be reduced compared to the limestone in its ideal, clean condition.

Beyond the blackening of walls and windows, modern restoration-related obstructions should also be noted as potential sources of daylight modification. Some light scaffolding was present near Window 42 and 37 (see Figure 4.2 below for window numbers) during the winter measurements, but this was neither extensive nor dense enough to provide a major obstruction to light infiltration from these windows. No nave clerestories were covered or affected by

scaffolding; however, further removed from the nave, during the January 2008 measurements the south rose and lancets were boarded up and choir clerestory windows 103, 104, 105, and 106 (see Figure 4.25) were also covered during both winter and summer measurements. In short, there are virtually no contaminations from windows dating from later than the early thirteenth century except in architectural bays adjacent to the Vendôme Chapel (Window 40).

The clerestory represents a major source of light for many interiors, and its current decreased transmittance ensures that the interior is darker than originally intended and that the nave lighting is likely dominated by side aisle windows. However, it will be shown (below in Section 4.2.1) that under cloudy conditions, and with the high elevation of the nave vaults, the clerestory contributes relatively little to the nave interior illuminance (~1-2 lux in Tours choir with an exterior horizontal illuminance of approximately 7000 lux, typical of a relatively bright cloudy winter day). Thus, with values at or lower than 7000 lux for most measurements taken in Chartres, the darkened clerestory was not considered a major component of the nave daylight factor contribution. However, with direct solar illumination particularly prominent at the clerestory level (as seen at Le Mans), the contribution of coloured clerestory windows to the detectable ambient solar lighting is more extreme (see results for León in Section 4.4.2). Therefore, caution should be applied in evaluating measurements taken in the cathedral interior during a sunny day, as the current blackened state of the windows severely limits the infiltration of direct sunlight (Figure 4.1)

The daylight factor results are presented in Figure 4.2, and readings (discussed but not illustrated) were also taken in the interior under late spring, partly cloudy conditions with illuminance values modified according to the Instrument 2 to Instrument 4 conversion discussed in Appendix II). The partly cloudy measurements were made in the mid to late afternoon, at a time when most of the direct sunlight entering the cathedral was coming through the (restored and relatively clear) west rose and lancets. Horizontal illuminances under the partly cloudy conditions varied largely between 6 and 7 lux in both the side aisles and nave (during cloud passes over the solar disk, interior illumination was lower by 2-3 lux). Because the sun's direct rays penetrated the west rose during the time of observations, most areas of the cathedral outside of the nave were lit by apertures receiving predominately diffuse illumination. Illuminance measurements were also taken on a party cloudy day (with the solar disk always fully exposed during measurements between 1114 GMT and 1420 GMT on the summer solstice (21 June,

2008). On this date values were makedly lower (2-4 lux in the nave and side aisles), likely due to the very high elevation of the sun and minimal penetration of direct sunlight into the cathedral (contrary to the likely winter pattern of higher solar illumination, as suggested by results for Bourges Cathedral in Section 4.1.4). Without regard to the aesthetics of sunlight across the windows, the exceptionally dark conditions would suggest that cloudy skies on summer middays would likely provide greater interior illumination than sunny skies. In this way Chartres provides an important counterexample to other cathedrals with an eastward or southeastward orientation, which in the summer have patches of direct sunlight aligned along the floor in the centre of the nave (Troyes) or choir (Evreux, Le Mans). Chartres exhibits darker values near ground level on the summer solstice due to its northeastward orientation. At midday on the summer solstice sunlight patches fell directly in the south transept and narthex rather than in the nave or choir, resulting in markedly lower illuminances in the nave on this date than for other times of the year.

More data from Chartres also illustrate the likely contribution of open doors to shallow low-level illumination in the interior. On 2 June, 2007, the west front door was opened at 1519 GMT on a clear day, and much higher illuminances were found deep into the nave. Instrument 1 readings revealed horizontal illuminances of 46 lux in the first architectural bay of the nave and 28 lux, 12 lux, and 8 lux in the centres of the subsequent nave bays to the east. Thus, only in the fourth architectural bay of the nave, deep into the interior, does the ambient horizontal illumination return to normal, expected levels. Elevated luminances were also observed as far as the crossing when the north transept doors were opened around 1400 GMT on 21 July, 2008. Thus, when the two transept and west front portal doors were opened during the Middle Ages, the light from open doors may have at times provided enhanced interior illumination in the lower levels of the church, allowing for adequate lighting and high visibility in the western nave and transepts.

Under cloudy conditions (with doors shut), the daylight factors calculated for the nave and side aisles were extraordinarily low, varying largely (see again Figure 4.2) between 0.02% and 0.05%. The fifteenth century Vendôme Chapel window appears to provide brighter conditions in the adjacent side aisle than in other bays, but the ambient illumination in aligned parts of the nave is not exceptional as demonstrated by south-facing vertical daylight factors (not shown) in the nave, which are equivalent across most of the nave architectural bays. Similarly, under the largely diffuse lighting of the partly cloudy skies during the spring analysis,

anomalously greater lighting in the bay adjacent to the Vendôme Chapel is evident with a horizontal illuminance of 9 lux and south-facing illuminance of 13 lux, compared to typical values of 6 lux for both in adjacent bays. In addition, the south-facing luminance in the aligned nave bay is 9 lux (as compared to the surrounding 6-7 lux of other bays), which is notable but less remarkable (and thus the Vendôme Chapel does not appear to substantially influence the broader nave lighting design).

However, the intersection of light from the west rose and its associated lancets with the side aisle lighting does appear to play a significant role in nave illumination. West 45°-facing daylight factors increase from ~0.00% in the first two bays of the nave to 0.02% in the next two to 0.04% over the centre of the labyrinth and the next bay north, followed by a decrease to 0.02% for the remaining nave bays. The west vertical daylight factor (VDF) registered values above zero in only two locations—the centre of the labyrinth (0.04%) and the bay to the west (0.02%). Despite measurement instability, the horizontal daylight factors are also greater between the western edge and center of the labyrinth than in most other parts of the nave. Similarly, the illuminance measurements under mostly sunny conditions on 12 May, 2007 and 21 June, 2008, demonstrate that some of the nave's highest illuminance values occur at the labyrinth and the bay east of the labyrinth, gradually decreasing toward the crossing and west front. This is despite the fact that sunlight patches from the west rose project onto the narthex floor around 1400 GMT during the summer solstice. Thus, the centre of the nave appears to be region of greatest daylighting for both sunny and cloudy conditions. A similar phenomenon, an accumulation of light in the central portion of a symmetric, high-vaulted space, was also observed in the daylight factors for the choir of Évreux (see Section 4.3.1). As one of the focal points of the cathedral during the Middle Ages, the labyrinth's location in the region of maximum nave illumination might have had strategic value. Therefore, these findings suggest that architectural lighting and its capacity to provide adequate illumination to particular features of an interior was likely a deliberate concern in the construction of cathedrals such as Chartres.

During this analysis, horizontal daylight factor measurements were performed twice under an overcast sky. However, measurements in the second round of observations appear to have been conducted (at least partly) under a CIE Overcast Sky 4, with brightening toward the sun as indicated by visual observations from the outdoor observer (west-northwest in the axial directions of the church). This would likely contribute to an overestimation of the daylight factor

in some locations. For example, many measurements in the nave registered 0 or 1 lux for 4000 lux exterior horizontal illuminance but 4 lux for 5400-6000 lux exterior horizontal illuminances conducted later during the brightening sky. The two measurements were averaged together, but in all but a few cases the average value is more than 0.015% DF (a randomly-selected precision threshold) away from the two absolute measurements. This leads to some instability in the interior daylight factor averages, and that, along with time errors, instrumental errors, and artificial light subtraction, may cause the average values to be skewed away from the actual DF value (and perhaps an overestimation, especially on the north side of the nave where the unequal brightening can be observed compared to the south side aisle despite similar window orientations and transmissivities). For example, three HDFs are available for the centre of the labyrinth, already determined to be one of the brightest points in the central nave, and they provide an average daylight factor of 0.03%. For comparison, the highly precise average (between two measurements) outside of Window 42 at 0.04% suggests that the side aisle may be slightly brighter, due to their closer proximity to the side aisle windows, than parts of the nave, and this corresponds broadly with the nave-only (minus the west front) simulation of Chartres lighting in Wallace et al. (1989). However, despite limitations in interpreting our results to a highly accurate degree, the range of values associated with the Chartrain daylight factors are consistent with similar measurements under full-colour conditons (presented below) in Strasbourg, Tours, Bourges, Le Mans, and Angers (not shown).

4.1.2 Strasbourg Cathedral: A Full-Colour Nave in the Holy Roman Empire

In many ways Strasbourg Cathedral provides an alternative architectural and aesthetic vision to that of Chartres. The broader glazing scheme of the cathedral possesses a mixture of Romanesque and Gothic glass from the twelfth through the fourteenth centuries, thus preserving one of most complete colour-dominated programs from the Middle Ages. The Romanesque nave was rebuilt largely from the mid-thirteenth century into the fourteenth century, and much of the glazing in the clerestory dates from this time period (Beyer et al., 1986; Hérold and Gatouillat, 1994). Romanesque glass, however, was reused in the Gothic cathedral, particularly in the north transept and the north side aisle. Much of the glass in the south aisle dates from a reconstruction during the fourteenth century (following a fire that destroyed most of the glass in the aisle-level lancets), and it carries on the largely full-colour tradition of the original south aisle windows (of which only the tympanum rosettes survive) (Beyer et al., 1986). In general, Strasbourg also

affords one of the best-preserved examples of the Rhenish colour tradition, which was often strongly divergent from the deep, saturated red and blue-dominated programs more common near Paris (Hérold and Gatouillat, 1994; Grodecki and Brisac, 1985). Specifically, Rhenish glass often used more transmissive colours (see Section 4.1.2 and 4.5), such as yellow, green, white, and light blue, as seen in the cathedral clerestory; however, this brighter glass does not always preserve its original translucency, especially in the south aisle windows. On the other hand, brighter modern restoration panes (scattered but numerous in the nave clerestory and north aisle, for example) currently installed in the windows probably help counteract the darkening effect caused by the decay of the original windows.

The sources of contamination lighting in Strasbourg are also different from those of other cathedrals. Unlike at Chartres, the Gothic construction was not fully completed until the Late Gothic period; this is manifested in the interior lighting of the cathedral through the Flamboyant rose window dominating the west facade, which was glazed (late fourteenth century) largely in luminous whites, yellows, and greens but is now filled predominately with modern glass (Hérold and Gatouillat, 1994). Transparent modern glass is also present in the west-facing lancets of both the Chapelle St-Laurent and Chapelle St-Catherine, which flood these particular chapels with excess light (as a consequence, no measurements were taken in them). In addition, the triforium level of the nave retains little of its original glazing, filled today with predominately modern coloured glass. However, its contribution to the illumination of the cathedral is likely small, as the triforium composes only a small proportion of the total glass in the nave. In addition, the south aisle windows were in relatively poor repair at the time of measurements; each window retained the majority of its glazing, but several panels were removed from every window as well for restoration (and replaced with translucent brown nylon material that did not appear to be much more transparent than the panes of original glass). Although they are not significantly blackened like the choir clerestory of Chartres, the south side-aisle measurements are also probably affected by the overall decay of window panes. In addition, Windows 11, 13, and 15 (in Figure 4.3) in the north side aisle were scaffolded and covered at the time of measurements, and this had an effect on both the north vertical and horizontal daylight factors in the aligned architectural bays of the nave.

Outside of Window 15, scaffolding between the nave and side aisle was also present, and thus no measurements were made in the adjacent nave. However, Windows 7 and 9, also in the

north side aisle, were uncovered and appeared to be highly translucent. Similarly, the nave clerestory windows, unlike at Chartres, were also in relatively good repair. During the artificial light subtraction, tapestries were hanging in the upper part of the side-aisle vaults, and while this would cut off some of the artificial lighting from the upper nave, it was determined that the nave and side aisle lightings were both dominated by artificial candle fixtures (which were in full view of the illuminance meters). In fact, the tapestries might provide a slight overestimation of artificial lighting due to some reflection off of back of tapestry from the light fixtures directly below. It should also be noted that the interior surfaces in Strasbourg possess somewhat different properties compared to other cathedrals. For example, instead of light grey limestone, the cathedral is constructed with a lower reflectance brown-reddish stone. In addition, the vaults of the nave and side aisles are presently painted white. These would, in turn, affect internal reflections.

Horizontal (Figure 4.3a) and vertical (Figure 4.3b) daylight factors were calculated (from one round of observations) under overcast stratus cloud cover, with a particularly good exterior hemispherical view and slow variation in horizontal illuminances. The results indicate that, despite the different sources of contamination and error (which produces variations from the original medieval interior lighting design), the range of daylight factors remains essentially the same as that of Chartres, largely between 0.02% and 0.05%. Also like Chartres, the central nave appears to be brighter than areas to the east and west, and this is particularly evident as daylight factors drop off moving toward the dark Romanesque choir (which is pierced only by small window apertures). However, it is also clear in this case that unequal lighting from Window 7 and 9 contributes to increased levels of interior lighting in the central nave, as is evidenced by elevated north VDFs in the two aligned nave bays. Given the fact that the north side aisle Windows 11, 13, and 15 are covered, the north-facing VDFs in the three westernmost architectural bays east of the narthex in the nave and south side aisles speak to the contribution of the choir clerestory windows to lighting in these directions, which ranges from 0.038% to 0.045%. This is much greater than both the contributions of the clerestory and opposite lower windows to side aisle lighting in Chartres during cloudy winter measurements, which produced nave-facing VDFs of zero in most cases, with a few readings near 0.020% (the only comparable reading, at 0.045%, is in the north side aisle across from the Vendôme chapel). Thus, for Strasbourg clerestory lighting in the side aisles appears to be substantial, perhaps on account of

larger window sizes, greater glazing transmission (less clerestory blackening), and luminous colour palette of the cathedral's windows.

In addition, the south side aisle has similar HDFs as the nave, but north-facing VDFs indicate that much of this illumination is probably coming from the nave clerestory, as the south VDFs are much lower by comparison. The opposite is true in the north aisle, where the window (rather than the wall below) dominates these readings. In particular, north VDFs toward the relatively translucent north-aisle windows are greater in this section of the cathedral than those facing the nave to the south. In addition, north VDFs in the south aisle spike 0.01% to 0.02% in bays aligned with Windows 7 and 9 compared to bays aligned with covered windows in the north aisle, suggesting that the strong illumination from these aisle-level windows renders a measurable effect across the nave. On the other hand, the more opaque windows of the south-aisle clearly do not provide significant contributions to the north side aisle's south-facing VDFs (which are comparable to north VDFs in the south aisle facing the boarded north aisle windows). The two uncovered north aisle windows also likely contribute to elevated west VDFs in the three architectural nave bays west of the choir.

The north side aisle windows that exert significant influence on nave lighting may provide important insights into the original lighting aesthetic of the building as well as the lighting capacity of Germanic coloured stained glass. Despite some scattered Renaissance fragments and modern contributions, including the thin, modern white lancet borders, these windows retain a large proportion of their original medieval glass (Beyer et al., 1986). However, the daylight factors adjacent to them (being close to 0.08%) are much greater than for most locations in the proximity of a group of coloured lancets (see Bourges below). The clue to their relatively high clarity compared to other windows likely derives in part from the abundant use of white glass, notably in the Gothic contributions provided by the lancet canopies and the tympanum above. Also, unlike most thirteenth century aisle-level windows in France, the lancets are filled with large-scale figures containing relatively large panes rather than the small, gem-like panels of mosaic glass, and thus they probably transmit a greater quantity of light in a manner more likely to be seen for clerestory windows. In addition, the iconography of these windows have also been linked to a preexisting Romanesque program (Beyer et al., 1986), and their clear light blues and yellows (with reds playing a significant but not a dominant role) suggest the importance given to translucency in Romanesque glazing. The use of more luminous

colours in the glazing of the Holy Roman Empire had been established from the birth of the Romanesque glass tradition, as seen in the example of the Old Testament prophets in Augsburg. Thus, clearly German churches could continue to use colour-dominated glass while admitting the quantity of light comparable or just slightly less than the white-dominated programs of France under cloudy conditions. In other words, the lighter colours used in the German glass programs would not necessarily need to undergo the same reaction against their coloured windows under cloudier conditions as their French counterparts. These issues are further addressed in Section 4.5.

In addition, the measurements in the north aisle also provide potentially important implications for the illumination of the Strasbourg nave during the Romanesque period, one of the few monuments from this time we know with certainty to have been glazed. While Strasbourg's eleventh century nave may not have had frescoes and other religious ornamentation (beyond the reach of candlelight) that required daylight illumination in order to be seen, the clarity of the original glass suggests that the structure (even with smaller apertures) likely obtained significant lighting gains from the highly translucent colours used, especially under direct sunlight. The persistence of the German Romanesque tradition through the beginning of the fourteenth century in both architecture and stained glass, over a century after France and England had largely converted to the Gothic style, may have also contributed to the ongoing importance of Romanesque-stylized (*Zackenstil*) coloured glazing and the delayed (but eventual) acceptance of the grisaille revolution (also discussed by Sherrill, 1927, and Grodecki and Brisac, 1985). In many Gothic windows, however, grisailles played an increasingly important role at the end of the thirteenth century and beginning of the fourteenth century. Examples include Cologne Cathedral and St-Thomas in Strasbourg, which both hosted band windows possessing a lower border of figural coloured glass accompanied by a field of grisailles across much of the rest of the aperture.

4.1.3 Bourges: A Full-Colour Ambulatory

Bourges cathedral contains one of the few well-preserved early thirteenth century full-colour ambulatory programs in Europe and was rigorously analyzed in this study. The structure possesses an originality and harmony in its architectural design that provides a counterpoint to Chartres (Mark, 1985), and the glazing program itself, noted for its rare iconographical coherence, demonstrates stylistic tendencies from both northern and south-central France

(Grodecki and Brisac, 1985). The aisle-level windows are positioned closer to the floor (not far above head height) than in most Gothic cathedrals (for example, Chartres), and thus the figural scenes are highly legible. The stained glass dates largely from the period 1210-1215, and despite some controversial restoration attempts in the nineteenth century (Grodecki et al., 1981), the majority of the windows remain intact and were in good preservation at the time of observations.

There are several sources of contamination lighting in the cathedral, most of them in the nave, constructed later in early-mid thirteenth century and largely glazed over the course of the fourteenth and fifteenth century (with some modern replacements). While nave lighting is far removed from the wide and cavernous outer ambulatory, the focus of this study, there are important sources of light from modern glass to consider in the ambulatory as well. The choir clerestory and triforium apertures retain large quantities of their original thirteenth century glass, which is especially well preserved on the north side of the choir. However, Windows 104, 106, 108, and 110 (labeled in Figure 4.5), stretching across much of the south triforium, contain nineteenth century white lozenges. This affects the lighting of the north ambulatory more directly and the south ambulatory through the reflection of bright sunlight admitted by these windows off the choir piers and stonework toward the south ambulatory. Another important consideration is the aforementioned placement of the ambulatory windows closer to the ground as compared to most other French gothic cathedrals; in such cases the illuminance meters intercept more direct lighting rather than deep clerestory-type inter-reflections.

Only approximate daylight factors could be determined in Bourges Cathedral due to weather limitations and the availability of only one observer at the time of a consistently overcast period. However, three rounds of measurements were taken under different types of overcast conditions (patchy overcast, overcast with brightening toward the sun, and CIE standard overcast sky conditions), and the procedure for estimating the HDF values presented in the following figures is given in Appendix III. Figure 4.4a shows the non-averaged daylight factors calculated for one round of observations during a CIE standard overcast sky, and Figure 4.4b presents averaged values between the standard overcast sky and the overcast sky with brightening toward the sun in the north ambulatory, with high precision average measurements shaded in grey. These daylight factors demonstrate remarkable consistency with the quantity of lighting provided by thirteenth century coloured programs in other cathedrals (Chartres and Strasbourg above) with different orientations. This is especially true in the south aisle, where

daylight factors largely range between 0.03% and 0.05%. Moreover, these values are relatively stable. For example, at Location 2 on Figure 4.5 three overcast measurements were taken. Even with the likely underestimation provided by the patchy overcast sky, the average of the three measurements at Location 2 (0.038%) and at Location 7 (0.035%) are both highly consistent with each other and do not diverge strongly from the values presented in Figure 4.4a and 4.4b.

Daylight factors increase in the architectural bay adjacent to the apse chapel, which is dominated by Renaissance glass, and the highly cavernous nature of the ambulatory likely facilitates higher daylight factors (due to internal reflections) in nearby regions of the ambulatory (see Figure 4.5). The slightly higher daylight factors on this side of the cathedral are probably attributable to some combination of the brighter triforium-related direct lighting in the north ambulatory and the characteristics of the glazing. The radiating chapels of Bourges, which are narrower than most others analyzed in this study and are provided with a concentrated, tall arc of coloured glass, also create an environment of higher illumination where daylight factors in the south ambulatory are concentrated at 0.06% to 0.07% and in the north ambulatory are closer to 0.1%. This design provides deliberately higher illumination for devotional shrines placed in the chapel as well as a narrative background on which worshipers could meditate.

In order to demonstrate the seasonal effects of direct sunlight on the ambulatory of Bourges, clear sky measurements were taken both in the late spring and winter at a similar time of day. However, due to restrictions associated with the weather, the sun’s zenith position was closer to an eastward orientation during the summer than during the winter measurements. The summer and winter illuminance measurements are given in Table 4.1. The results are presented in absolute terms with respect to Instrument 2 (see Appendix II), which underestimates values by about 4-5 lux compared to Instrument 4 (daylight factors were calculated using Instrument 4 data). Therefore, in the textual discussion the table values are rounded up by 4-5 lux when making comparisons to expected cloudy measurements if Instrument 4 values are not available for the observation. The high horizontal illuminance values in the south ambulatory reveal that even on a brighter cloudy summer day, illuminance values (probably 10-12 lux) likely remain below that of a sunny summer day (15-36 lux). However, late spring sunlight under high solar angles also appears to provide the greatest illuminance to a relatively constrained region. Clearly at Location 9 during the spring measurements the instruments received direct solar illumination from the window, with interreflections providing greater values to adjacent portions of the

ambulatory (as demonstrated by the rapidly increasing east-facing illuminances between locations 4 and 7). In addition, because the sun rises in the northeast and sets to the northwest between the spring and autumnal equinoxes (and the cathedral is oriented on an east-southeast direction), much of the north and south ambulatory profits from elevated, focused lighting during at least one part of the day, and this illumination far exceeds overcast lighting. Conversely, the semicircular orientation of the ambulatory provides an environment where at least one region of the ambulatory has high illuminance values during much of the day.

In the winter, by contrast, the interior lighting under the prevailing sunlight is much greater for the same locations analyzed during the summer. This is clearly due to the low elevation of the solar disk, which orients the sun's direct rays nearly perpendicular to vertical-facing window planes (during most of the winter day) and which thus provides greater illumination for most of the south-facing apertures. A similar pattern would also be present during other times of the year after sunrise and before sunset. The greater illumination produces a broader area of higher illuminances in the south ambulatory and deeper sunlight penetration into other parts of the cathedral (see Table 4.1). There are no single points of strongly concentrated illumination (similar to Location 9 during the summer measurements) but instead there is an extended region of horizontal illuminances between 37 and 123 lux across the south ambulatory (in the summer, these values were only seen in a much smaller, restricted area of the ambulatory). Elevated south-facing illuminances associated predominately with reflections from the brighter south ambulatory extend to Location 15. In the north ambulatory (Table 4.2), locations 16, 17, 22, 23 and 24, exhibit influences from higher illumination associated with the modern triforium to the south (south-facing illuminances of 34-47 lux). However, as shown in Table 4.2, locations 19, 20, and 21 are not as strongly illuminated by the triforium (with north-facing illuminances of approximately 15-18 lux), and Location 20 has only sunlit south ambulatory thirteenth century windows in its view (although inter-reflections from near the Lady Chapel undoubtedly make a contribution). The three abovementioned points have horizontal illuminances close to 10 lux, nearly double what would be expected on a bright cloudy winter day (6 lux) with an exterior horizontal illuminance of 10000 lux.

Therefore, lower winter sun angles provide an expanded region of high, more evenly-distributed interior illumination in the south ambulatory. This in turn provides deep diffusion from the south ambulatory (see Figure 4.6) well into the choir (in the absence of a choir screen)

and north ambulatory such that illumination is brighter even on the north side of the cathedral under sunny conditions than for most cloudy conditions. The importance of greater solar light penetration from low-level chapel windows when provided with low winter sun angles was also demonstrated in the nave of Bourges. Directional measurements to the south were much greater than during the summer due to deeper penetration of sunlight from the aisle-level fifteenth century windows into the interior, which exceeded 130 lux (vertical, facing south) as far away as from the centre of the nave. The general increase in illumination in the nave of Bourges Cathedral from summer (16-20 lux) to winter (30-60 lux) (not illustrated), while partly related to the differential zenith angle of the sun between the summer (1016-1019 GMT) and winter (1136-1155 GMT) measurements, is probably not dominated by increasing clerestory-level lighting (due to expected higher solar illumination in the summer at low elevations as discussed for Le Mans similar choir orientation (see Section 4.1.4 below)) and instead controlled by aisle-level windows. However, low elevation triforium sunlight reflections (seen in Figure 4.6) may have important impacts on the nave observations.

Furthermore, for an ambulatory bay whose chapels and adjacent windows are facing away from the sun, clearly (as demonstrated above for the modern triforium windows) the contribution of solar lighting from clerestory and triforium windows can be significant. This phenomenon is perhaps most vividly demonstrated by photographic evidence from the south ambulatory of Le Mans Cathedral, which has a similar double-ambulatory layout as seen in Bourges. Figure 4.7 was taken in Le Mans's south outer ambulatory (850 GMT, 30, June, 2008) when the north choir clerestory and ambulatory were receiving direct solar radiation, and it demonstrates a broad area of enhanced solar lighting associated with coloured patches on the south ambulatory floor (with sunlight originating from the choir clerestory). These colour patches covered much of the floor space of the western architectural bays of the south ambulatory at the photograph was taking, providing enhanced illumination throughout this section of the cathedral. Furthermore, Figure 4.7 also indicates that the orientation of one of the eastern radiating chapels allows it to capture direct sunlight and transfer it into the eastern bays of the south ambulatory. Thus, clearly the cathedral's orientation allows it to provide enhanced illumination under sunny conditions even in parts of the interior that are farther removed from windows receiving direct solar radiation. For an ambulatory passage lit predominately by opposite clerestory windows, this illumination would probably be greatest when solar angles are

moderately high, especially during the early-mid spring, late summer, and early-mid autumn months when patches of direct sunlight with illuminances on the order of 200-1000 lux can reach the floor and arcades of the opposite outer ambulatory for extended periods of time. In the winter the brightest sunlight patches from the clerestory tend to fall predominately on the walls of the choir clerestory and triforium (the ambulatory may still receive strong solar lighting from triforium windows), and in the late spring and early summer such enhanced illumination is more temporary as the sun rises quickly in inclination and bright solar patches from the clerestory move to the centre of the nave and choir by midday. In Bourges, locations in the north ambulatory experience large sunlight contributions from the modern triforium, and coloured glass in these windows under strong solar illumination during the Middle Ages would have reinforced the higher north ambulatory illuminances under sunny conditions (although likely to a lesser extent than the current clear windows do). In addition, the deeper penetration of the south ambulatory sunlight would have reinforced the north ambulatory illumination, especially in its eastern architectural bays. The north ambulatory measurements and supplementary photographs thus reveal that sunlight from the triforium and aisle-level windows of the south ambulatory was intended to penetrate the north ambulatory to ensure a more even, consistent interior illumination (particularly notable during the winter measurements).

The Bourges observations also reveal that illumination extremes between sunny and cloudy conditions are greater in the winter than in the summer. Because the strongest direct sunlight is very high for only a few apertures and their surrounding architectural bays in the summer, at any given moment much of the ambulatory not far from the source of direct sunlight may have illuminances equal to or greater than those of a bright overcast sky (for example, with an exterior horizontal illuminance of 30000 lux). However, in the winter, as has been demonstrated above, the deeper penetration of sunlight provides greater illumination under sunny conditions, even in the north ambulatory, than is expected for most cloudy conditions. In the south ambulatory, interior illumination may swing from 4 lux under a bright winter overcast sky to 100 lux or more when provided with sunlight. Thus, at least for the ambulatory, the Bourges example suggests that the large gap between sunny and cloudy interior lighting under full-colour stained glass programs would have been most marked in the winter. Therefore, an increase in winter cloudiness would more likely be associated with a general dissatisfaction with full-colour illumination.

This renders the possible trends in the NAO index established above particularly relevant to the illumination of full-colour versus white-dominated interiors. The conversion to whiter glass, beginning largely during the last third of the thirteenth century, appears to predate the rapid drop in the NAO index trend given in Proctor et al. (2000). However, dating uncertainties in these proxies along with other indicators (for example, Icelandic records) of a deteriorating climate starting as early as the beginning of the thirteenth century must also be considered, especially when taking into account the experimental and highly versatile nature of window glazing (as a relatively new medium) during this time period. In other words, cloudy conditions might have provoked a rapid response, i.e. a correction of the illumination associated with an increasing awareness of cloud cover lighting, for some interiors. In addition, many areas persisted in the full-colour tradition until the fourteenth century (Grodecki and Brisac, 1985), but hardly any full-colour programs were commissioned in France after the rapid and nearly permanent decrease of the NAO in the first decades of the fourteenth century. Therefore, white glass took on a more prominent role than ever before in programs such as in Évreux Cathedral, and mosaic glass was virtually abandoned by this time. Southwestern German glass, after adhering strongly to the coloured tradition, also began follow the whitening trend seen elsewhere in northern Europe over the course of the fourteenth century. Thus, given the likely shift to a more negative phase of the NAO during the fourteenth century, it seems possible that a preference for white glass during this time period was in part a reflection of a greater awareness of lighting needs under cloudy conditions. Colour only reestablished its preeminence after flashed glass and enamels (accompanied by improvements in the clarity of white glass) afforded higher transmissivity glazing by the fifteenth century.

4.1.4 Le Mans: A Full-Colour, Rayonnant Choir

While Bourges provides a well-preserved outer ambulatory dominated by illumination from thirteenth century full-colour windows, Le Mans affords an excellent opportunity to examine a choir from the coloured tradition. The cathedral once likely possessed a remarkably complete coloured program, with Romanesque glass in the nave and rich, twelfth and thirteenth century glazing in the Rayonnant choir, ambulatory and radiating chapels. Unfortunately, most of the side-aisle windows were destroyed, with some surviving twelfth and early thirteenth century panels placed in the Lady Chapel or scattered throughout the ambulatory lancets (Grodecki et al., 1981). Therefore, most of the glass in the present-day ambulatory is coloured

but dates largely from the nineteenth century. The clerestory and triforium windows of the choir are largely original, being from the third quarter of the thirteenth century, with the exception of Window 208 in the south choir clerestory, which was destroyed in a windstorm and replaced in the nineteenth century with richly coloured glass modeled after the surrounding windows (Grodecki et al., 1981). Despite the cathedral's adherence to full-colour principles, which would seem to link Le Mans to contemporary Parisian works, Lillich (1994) has established the independence of Le Mans and its program as part of a Western (French) tradition in glazing that is highly distinguishable from Parisian models (which were employing saturated coloured programs at the same time, reflected in the palette at Tours) (Lillich, 1975). In this context, Le Mans is especially unique with regard to the clerestory windows' subject matter, which pertains largely to local saints (Lillich, 1994).

While the choir glazing is particularly well preserved, there are also several sources of contamination to consider. For example, the cathedral's thirteenth-century chevet and Romanesque nave are today separated by a Late Gothic (fourteenth century) crossing and transepts, which possess massive windows filled predominately with high translucency stained glass (fifteenth century and modern), some of which directly illuminate the choir and ambulatory. These larger windows and their predominately uncoloured glass probably were intended to provide more light to the nave and choir. In turn, this might have been the product of a fifteenth century desire for more light in the cathedral without destroying precious glass from earlier periods. In addition, the radiating chapels of the ambulatory were probably modified in the sixteenth century before the Huguenot assault on the windows of Le Mans in 1562 (Grodecki et al., 1981). Today, internal reflections from the strong illumination in the nave (associated with modern, high translucency windows filling the Romanesque apertures), as well as direct lighting from the anachronistic crossing and transept clerestories, provide the dominant contaminations on the choir lighting. A tall gate, curtain, and set of stalls extending along the north and south boundaries of the choir, along with an obstructing altar under the hemicycle, block most direct lighting from the ambulatory, providing an opportunity to analyze the contribution of the triforium and clerestory windows to choir lighting while ignoring the surrounding modern glazing at the aisle level. Interior illumination in the choir/altar was probably of particular interest in the Middle Ages, as it represents the sacred centre of the church. In addition, lighting

in the choir provides a reflection of the illumination associated with the hemicycle, the visual focal point of the cathedral.

Daylight factors were calculated for the interior under an overcast sky (with rain) and slowly brightening cloud cover. Figure 4.8 demonstrates that the choir of Le Mans, even with the modern contamination lighting, has daylight factors (0.03 to 0.04%) within the same range as those computed for Chartres, Strasbourg, and Bourges. Moreover, the daylight factors in the choir are nearly equal to those at corresponding locations in the choir of Tours Cathedral (which has comparable contamination sources as Le Mans). Winter and summer measurements, again taken at similar times of the day but also when the sun was positioned at a slightly different zenith angle, were collected under clear sky conditions and are shown in Table 4.3 and Figure 4.9. The late spring measurements (1 June, 2007) were performed when south choir Windows 208, 210, and 212 received direct sunlight and the winter measurements (25 January, 2008) when the south hemicycle Windows 200, 202, and 204 were receiving direct sunlight. The summer measurements (30 June, 2008) were taken when much of the north choir clerestory and the northern half of the choir hemicycle was receiving direct sunlight.

Clearly, during both seasons all three points have elevated interior illuminances (within the range of 28 – 44 lux) under sunny conditions; however, unlike in the ambulatory, the choir does not demonstrate significant differences between winter and summer illumination, at least not as resolved at ground level. The late spring illuminance values appear slightly greater than those for winter, due in part to the position of the sun providing greater illumination for the southwest choir windows and the mostly modern glazing of the nave and transepts. Thus, the increased values may be partially attributable to greater contamination lighting from the west at the time of summer measurements, as the west-facing illuminances show the largest discrepancies between the two seasons while illuminances in the other directions remain similar in value. These results from Le Mans are quite consistent with data obtained from the inner choir of Tours under a hazy, mostly clear late spring sky between 1230 and 1245 GMT (4 June, 2007), for which horizontal illuminances ranged from 36 to 38 lux.

During the summer, direct sunlight around midday is more likely to be received (and reflected) at the lower elevations of the choir (closer to ground level) due to higher solar angles. This pattern is well-represented by our data in the cathedral of Le Mans from 30 June, 2008 (with the sun aligned with Window 201). In particular, the midday HDR luminance profile

presented in Figure 4.10d when compared to that in the winter (Figure 4.14a, with the sun correspondingly aligned with Window 202) indicates that the summer profile has broadly higher luminance values along the choir vaults and clerestory spandrels around midday. This may be due in part to a more evenly-distributed directional luminance profile of the sky in the summer associated with a higher solar elevation, in which windows not aligned with the sun receive greater illumination (as opposed to winter measurements when the brightest sky luminances are strongly weighted in one direction). In addition, most solar light patches at the time (just after 1000 GMT) were positioned along the floor and lower piers of the choir, at a lower elevation of the cathedral than the choir spandrels. This causes the midday summer profile to have lower south clerestory spandrel luminances (~20-30 cd/m^2). By contrast, in the winter measurements most of the received light is being directed below the vaults along the axis of the choir (causing the central hemicycle Window 200 to have an average luminance three times brighter in the winter measurement than in the summer measurement, both taken at the same location and tripod height). However, high luminance values (50-80 cd/m^2) are still present on the north clerestory spandrels in the winter 1050 GMT profile, much greater than the 20-30 cd/m^2 values on correspondingly-positioned south clerestory spandrels for summer observations in Figure 4.10d.

Early summer morning and midday illuminance data, provided in Table 4.3, also confirms that light becomes more concentrated at the low levels of the church during periods of high solar elevations. Despite much brighter illuminances along the vaults and spandrels of the clerestory during the early morning (see HDR luminance profiles in Figure 4.10a-c), this is the period of the lowest low-level illuminance values, which are quite comparable with the winter illuminance profile at the same location. In fact, the solar angles during the 733 and 815 GMT measurements are nearly equivalent to those during the winter, and as such the 718 GMT and 805 GMT luminance profile could also be viewed as representative of potential lighting levels in a full colour cathedral on a sunny winter day. In addition, the fact that the summer morning luminance profile of the cathedral is similar to that from January afternoon, and that the north clerestory glazing is largely original and in good preservation, suggests that the modern replacement glass in Window 208 does not significantly alter the interior daylight aesthetic of the cathedral. By summer midday (1000 GMT), the illuminance levels (70+ lux) have nearly doubled in the centre of the choir, much higher than the midday winter and summer morning

values. At Location 3 (see Figure 4.9), illuminance levels are very high because the measurements were taken under a patch of direct sunlight filtered by Window 201 hitting the floor. An even brighter, broad sunlight patch (see Figure 4.16c) adjacent to the lower part of nearby choir pier was documented through HDR as having a luminance of 30-40 cd/m^2, somewhat lower than typical values above 50 cd/m^2 in the early morning, perhaps in part due to the projection of individual light patches around midday across a greater distance than in the morning and thus onto a broader surface area. Therefore, with values above 400 lux received underneath this weaker light patch (associated with nearby surface luminances around 30 cd/m^2), at the level of the choir clerestory on a winter day or a sunny summer morning, similar or much greater (perhaps reaching 1000 lux) ambient illuminations would likely be detected. This pattern of strong solar lighting right at the surface from clerestories was also observed (not shown) on a summer midday (19 June, 2008, 1000-1100 GMT) for Troyes Cathedral, in which a row of bright sunlight patches were aligned down the centre of the nave.

During the winter, direct solar illumination admitted by the windows (such as those in the ambulatory) is probably greater throughout much of the day due to the solar disk's lower angle and more perpendicular orientation to the window plane (as seen in the ambulatory of Bourges). However, reflections of this sunlight occur at higher elevations (at the triforium and clerestory levels, see Figure 4.23) that are further removed from the illuminance meter. Under summer solar illumination, the penetration of direct sunlight is generally less deep in its horizontal projection, with more sunlight patches falling directly on the windowsill rather than piercing the interior. However, direct sunlight in these cases is also often more concentrated at lower elevations, leading to comparable ground-level illumination between the two seasons (except right at midday during the summer when illumination is markedly higher than in the winter for traditional eastward and southeastward cathedral orientations). Thus, in most instances the winter again appears to provide the greatest contrast between cloudy and sunny illumination. In particular, the 4 lux expected for a bright winter cloudy day contrasts markedly with the approximately 30-40 lux year-round sunny illuminances, whereas in the summer horizontal illuminances near 9-12 lux may be more typical on a bright summer cloudy day. As a qualification to this argument, however, thick cloud cover on a summer day has the potential to decrease illuminance values as much as for a bright winter day, and furthermore any cloud cover in the summer around midday will provide markedly reduced ambient low-level illuminance

compared to a sunny day, given the elevated illuminances as high as 70+ lux in Le Mans choir 1000 GMT on 30 June, 2008.

Another way choir hemicycle lighting can be understood at a level closer to the clerestory is by analyzing lighting in radiating chapels, which act like hemicycles on a reduced scale. In providing a continuous arc of lancets (with minimal wall space between the windows), observations associated with the Bourges chapels appear to be particularly pertinent to illustrating hemicycle lighting at the clerestory level of a thirteenth century Rayonnant choir. For example, at Location 2 in Figure 4.5, the chapelward (south-facing) measurement increased from 24 lux in the summer to 151 lux (both as measured by Instrument 2) in the winter, thus suggesting that a strong increase in interior illumination at the clerestory level of the choir would be provided in the winter over the summer. In addition, during the winter, measurements in the south ambulatory chapels afford a brighter locus of strong illumination at locations 3 and 8 (Figure 4.5) than in the adjacent ambulatory bays (locations 2 and 7 respectively), in both sunny and cloudy conditions. Thus, the choir hemicycle would also appear to be a region in which both direct and internally reflected light would be concentrated at the clerestory level. In addition, most choirs maintain this enhanced illumination throughout much of the day, as seen at Beauvais in January (results not shown). Due to the semicircular and predominately eastward or southeastward orientation of most cathedrals, the choir maintains direct sunlighting from sunrise until the late afternoon throughout much of the year and sometimes also in the late evening on dates closer to the summer solstice. In summary, choir illumination appears to be strongly enhanced (compared to most other portions of the cathedral) throughout much of the day when the solar disk is unobscured, thus maintaining the visual importance of the choir and its associated architectural forms. However, under cloudy conditions the prominence of choir architecture and lighting depends strongly on glazing transmission, and these issues will be further discussed in the following chapter.

4.2 The Grisaille Revolution

The importance of grisailles in the evolution of the Gothic style has long been a prominent topic of discussion and debate in stained glass literature. While more common starting in the second half of the thirteenth century, grisailles have always been an important part of cathedral interior light design (Morgan, 1983). Even predominately full-colour programs, such as at Chartres, incorporated a few modulating grisailles as part of its original program (Lillich,

1972). As demonstrated by Pastan (1994) for Troyes Cathedral, early thirteenth century grisaille-dominated windows were often tactically incorporated into the dark crevices between adjacent radiating chapels (and also often on a north-facing surface of the cathedral that received only diffuse radiation). Therefore, grisailles appear to have played a strategic role as equalizers of light in early Gothic chapels, suggesting that harmony in the interior illumination capacity of windows was a significant design concern for medieval architects and glaziers. Furthermore, in France grisaille windows are known to have cost only slightly less than coloured windows, thus keeping them from often becoming a measure of economic constraint (Pastan, 1994; Lillich, 2001). Some regions may have preferred grisailles more than others as a product of regional taste; for example, southern Champagne (Troyes) and northern Burgundy (Auxerre) incorporated several grisailles into their programs at the beginning of the thirteenth century when other projects (Chartres and Bourges, for example) were not producing them at all (Pastan, 1994).

However, the conversion of most of the window space to whiter glass in northern continental Europe provides a significant shift in both aesthetic and interior light design from past models, and the earlier tactical use of grisailles suggest that the broad shift to white glass at the end of the thirteenth century also had functional significance. In England, grisailles were often preferred over extensive coloured programs during the thirteenth and subsequent centuries, as suggested by the prevalence of early Gothic grisailles surviving in York and Salisbury (Marks, 1993) and textual evidence from Lincoln (Morgan, 1983; Raguin, 2003). The background cloudy climate of England, discussed in quantitative terms by Meerkötter et al. (2004) and Fontoynont (2002), would appear to confirm claims by Charles Sherrill (1927) and Lillich (personal communication, 2008) that the broader, cloudier climate of the British Isles was likely a factor in the English preference for whiter glass, even during the presumably higher-index NAO phases of the Medieval Warm Period.

In the Mediterranean basin, by contrast, few grisailles were used; sometimes coloured glass was adopted, such as in Assisi, Florence, and Siena, and alabaster was also used for major projects (as in Orvieto Cathedral), providing adequate illumination under sunlight but not for northern illumination (M. Lillich, personal communication, 2008). Even when grisailles were used in the Mediterranean, such as at Lyon, Narbonne, and Santes Creus, it was often significantly coloured, used to fill smaller apertures, and/or incorporated into mixed programs in

a manner similar to Auxerre Cathedral (Grodecki and Brisac, 1985; M. Lillich, personal communication, 2008). Despite relative consistency in the usage of grisailles in England and the Mediterranean, across northern France in less than a century coloured programs like at Le Mans and Tours were abandoned for nearly completely white programs like at Évreux, with the role and function of the grisaille window being revolutionized in the process. In addition, preexisting programs, such as in the ambulatories of Chartres (Lillich, 1972), Cologne (Raguin, 2003), and potentially Amiens (Sherrill, 1924), were modified with the inclusion of more grisailles during this time period. The permanent consequences for interior lighting associated with this 'grisaille revolution' are explored in the following chapter.

4.2.1 Tours and Cologne: The Effect of Grisailles on Choir Illumination

Tours and Cologne provide a particularly good juxtaposition of diverging interior lighting strategies at the end of the thirteenth and beginning of the fourteenth centuries. Both cathedrals represent the same stage in the evolution of Gothic architecture—Rayonnant—each containing a pierced triforium and characteristic wall of glass extending across much of the clerestory level. However, Cologne and Tours are highly independent in style from each other. In particular, Cologne Cathedral, one of the greatest construction projects in the Holy Roman Empire of its time, was part of the German tradition in glazing that was far removed from contemporary French models such as Évreux (this is reflected by the development of a band window variant rather than an adherence to the French band window formula) (Lillich, 1975). In particular, Cologne had retained its own stained glass tradition since the Romanesque period from which to draw examples. The glazing in Tours Cathedral primarily represents design strategy from the second half of the thirteenth century (work continued on the coloured windows until 1280) (Grodecki et al., 1981), whereas Cologne's choir clerestory possesses stained glass largely representative of the first third of the fourteenth century (Herbert, 1974). Cologne's clerestory glazing is particularly well preserved, in most windows retaining 60-95% of its original glass (which is in an excellent state of preservation) (Herbert, 1974). Tours' choir clerestory windows are heavily restored but were well-maintained at the time of observations (Grodecki et al., 1981). Stalls and/or gates in the western half of both choirs block direct illumination from western ambulatory windows, but both choirs are also influenced by light from the radiating ambulatory chapels. Additionally, the two cathedrals contain similar source regions of anachronistic contamination lighting; both are dominated by modern glazing in their

naves and maintain largely nineteenth century decorative grisailles in their choir triforium levels. In addition, where Tours's ambulatory chapels are filled primarily with coloured glass (much of it moved there from other churches in town), Cologne's ambulatory retains a mixture of modern glass and band window-type, canopy-dominated glazing from earlier periods.

There are also important distinctions between the two cathedrals, especially with respect to their cavity ratios. In particular, Cologne is a broader structure than Tours, with a choir width of 15 m and length of 41 m (compared to Tours's 11 m and 30 m respectively). Therefore, incoming light spreads out over a greater surface area in Cologne, resulting in lower ambient lighting at any given point. In addition, the choir vaults of Cologne (46 m) are much taller than in Tours (29 m), and the clerestory windows of Cologne are 16.7 m high and in Tours are 10.5 m high. The greater height of the clerestory windows of Cologne Cathedral away from the observer likely cause internal reflections to play a greater role in the measurements than direct lighting; however, a major source of inter-reflections—the vaults above and side walls opposite the windows—are further removed from the illuminance meter in Cologne compared to Tours. With decreased distances between the illuminance meter plane and reflective surfaces/direct lighting sources, the choir of Tours should theoretically be markedly brighter than that at Cologne if provided with the same glazing. In addition, it should also be noted that while Tours retains its original stone vault surface, today's Cologne cathedral vaults are painted white (the original surfaces in Cologne have a stable average reflectance that is 0.76% of the reflectance of the white paint, based on thorough sampling from several separate luminance profiles). Given the similar reflectances between the limestone and white paint surfaces, along with the whiter appearance of Tours's vaults relative to that of Cologne's sidewalls, we do not expect this to be a major factor in the differences in illumination between the two cathedrals.

The results of daylight factor calculations are presented in Figure 4.11; only one round of observations was performed in Cologne (under very stable horizontal iluminance conditions), and two rounds were averaged in Tours (and all daylight factor calculations in Tours were highly precise, producing a representative average). The greater illumination associated with the lower elevation, more compact Tours Cathedral is immediately apparent in the choir near the transept, where contamination lighting from modern windows in the nave and transepts clearly predominates. By contrast, in the vast interior of Cologne the contamination lighting from modern windows does not register notably brighter values near the crossing. The high daylight

factors in the choir near the hemicycle keystone does appear, however, to be due to anomalous light admitted by modern chapel windows in the western two chapels of the north ambulatory. In the inner choir of Tours, which is further removed from contamination sources in the nave, the daylight factors level off considerably, ranging from 0.025% under the hemicycle vault convergence to 0.049% at the edge of higher values associated with modern illumination. In particular, the values between 0.025% and 0.039% are co-located with similar values (0.030% to 0.038%) in Le Mans choir (approximately 34 m height, 12 m width, 33 m length), demonstrating remarkable consistency between these two coloured interiors. The inner choir of Cologne, on the other hand, is notably brighter, with HDFs ranging from 0.055% to 0.058%. This is as much as twice the illumination in the inner heart of Tours choir, in spite of the differences in geometry between the two cathedrals that favours greater illumination in Tours over Cologne. These results therefore imply that the grisaille clerestory provides a notable improvement in interior lighting, as much as double the low-level illumination seen in the full-colour aesthetic. In addition, this increase may be even greater if provided with lower cathedral vault elevations (see Évreux), which was a well-established trend during the Late Gothic period.

4.2.2 The Formalist Approach: The Effect of Grisailles on Architectural Lighting

The formalist argument provides an often-cited explanation for the conversion to grisailles and white-dominated programs in France and Germany at the end of the thirteenth century and beginning of the fourteenth century. It suggests that a desire to illuminate the architectural forms of the cathedral led to the introduction of whiter glass and eventually silver stain in the fourteenth century (Lillich, 1994; Grodecki and Brisac, 1985). With increasing architectural complexity in the fifteenth and later centuries, high translucency glazing continued to be important for providing adequate illumination of these architectural forms. The reverse argument can also be made; as glass became whiter and more ornamental, architectural decoration and window tracery began to take the place of historiated stained glass as a source of aesthetic interest (particularly in the Late Gothic or Flamboyant period). A directional causal relationship is thus hard to establish, especially considering that some Rayonnant interiors with intricate architectural decoration continued to employ coloured windows (for example, the choirs of Le Mans and perhaps at Amiens). Therefore, it is useful to analyze the performance of coloured and uncoloured Rayonnant programs to demonstrate their respective ability to illuminate architectural forms. As the visual focal point of most cathedrals, the choir was

deemed an appropriate region to analyze in assessing the validity of the formalist argument under different types of weather conditions. In this analysis, vignetting effects are largely ignored in the textual discussion. As most images are oriented similarly with respect to the choir, certain forms nearly always fall near the edges of the images and others near the centre. Thus, it is possible to make a valid relative comparison between the calculated luminance values of forms near the edges of different images taken with the same focal length.

In order to test how thirteenth century coloured glazing performs with respect to later interiors, we created an HDR photoseries of Le Mans Cathedral and St-Serevin in Paris during a period of direct sunshine (unobscured solar disk) in both establishments. The two churches possess a mixture of well-maintained medieval (the majority) and nineteenth century coloured glass. For the St-Serevin measurements, some altocumulus cloud cover was present to the west, but the east, north, and immediate south directions were mostly clear. In Le Mans the photos were taken under a typical CIE standard clear sky. The two churches are oriented in different directions: St-Serevin 20° south of east and Le Mans 54° south of east. Thus, a later afternoon measurement was required at Le Mans (1347 GMT, 25 January) to ensure a similar solar orientation with respect to the choir windows as during the measurements at St- Serevin (1236 GMT; 23 January). The illuminance in St-Serevin (45-52 lux) in the direction of the HDR photo series was greater than the 25-40 lux seen in observations in Le Mans choir during sunny conditions. Therefore, we know that more light is being admitted by the predominately fifteenth century windows, which is providing somewhat greater ambient interior illumination. However, as has already been established above, the intensity of solar radiation during the winter is strongest at and just below the level of the windows, and to a substantial degree the lower elevation of St-Serevin provides more intense illumination near the ground level due to the closer proximity of the apertures (as noted below in Section 4.3.2), the choir of St-Serevin has a signature of the hemicycle similar to those seen in chapels). In both cases photo series were taken under winter conditions, when solar illumination of the architectural forms of the side walls would be at their maximum.

Despite greater ambient lighting, there are relatively few differences in the illumination of architectural forms between Le Mans and St-Serevin. Looking at Figure 4.12a and 4.12b, it is clear that fifteenth century glazing in St-Serevin produces more intense bright spots on the arcade spandrels opposite windows receiving direct solar lighting, with luminance values of over

100 cd/m^2 across relatively large surfaces. In Le Mans Cathedral the corresponding spandrel luminances are constrained to 25-40 cd/m^2 with fewer and smaller bright patches near 100 cd/m^2. However, between the light patches in St-Serevin are equally large surfaces with luminance readings constrained to values equivalent to those seen in Le Mans. Additionally, these extended bright spots seen in St-Serevin do not exclusively illuminate architectural forms but rather also clearly fall on the opposite windows (and in doing so obscure them), as seen in Figure 4.13, producing the problem of backlighting (discussed below in Section 4.2.3). Therefore, we can conclude that the program at St-Serevin produces an improvement in lighting architectural forms opposite windows receiving direct sunlight when compared to Le Mans, but only in discrete, mobile patches rather than uniformly across the stonework. Also under sunny conditions (not shown) St-Serevin possesses on the south side clerestory bright streaks along the vault at 30 cd/m^2, which is markedly brighter than the 15-20 cd/m^2 luminances seen on the south side of Le Mans. However, this appears to be largely a function of glass translucency of the window border, with predominately white-border windows in the clerestory of Le Mans providing similar streaks of 50+ cd/m^2.

The lighting of Le Mans, while also retaining brighter patches, appears to provide somewhat more even luminances at the triforium level. This is true throughout the afternoon, as tested by photo series taken at 1041 GMT and 1347 GMT in Figure 4.14. For example, the intricate foliate decoration on the triforium reflects 6-7 cd/m^2, and during the afternoon this decreases slightly to 3-4 cd/m^2 as the solar disk becomes less directly aligned with the choir axis windows. The spandrels of the choir arcade that are not illuminated by direct sunlight also have remarkably consistent luminance values (~8 cd/m^2) between the two photographic analyses of Le Mans Cathedral's choir. Thus, we would not expect the illumination of these forms to change substantially during the midday period. For the corresponding choir arcade spandrels of St-Serevin (the right quarter of the original HDR image), the luminance values are surprisingly similar (also 6-8 cd/m^2). Additionally, St-Serevin's choir lighting (Figure 4.15a) appears to contribute little to the illumination of the complex vaulting in the ambulatory, with much less light received for the pine vaulting in the Parisian church than for the foliate triforium decoration in Le Mans. In fact, Le Mans's triforium windows are oriented in the narrow outer ambulatory so that they provide maximum illumination of the triforium foliage through internal reflections off of nearby vaults and piers in the narrow inner ambulatory. The intricately ribbed vaulting in

the hemicycle of St-Serevin is another manifestation of the increasing architectural complexity of the Late Gothic era. However, the luminances on the surfaces of this complex vaulting is essentially equal to or less than that for the hemicycle vault convergence for both of the profiles at Le Mans.

Another useful test on these findings is afforded by comparing the Le Mans afternoon HDR image with one from Beauvais (Figure 4.15b) taken around noon (CEST) with a similar solar orientation to its windows (the cathedral's axis is oriented just slightly south of east, allowing for an earlier measurement). While taking observations, direct solar illumination was received by the windows of the southeast hemicycle and south choir; in this group Windows 304 and 306 are particularly well preserved, retaining the majority of their original grisailles (Grodecki et al., 1978). Unlike in Cologne, however, many of the other band windows of Beauvais's upper clerestory preserve only a relatively small fraction of their original glass, with a substantial proportion of the grisailles and decorative glass redone during the modern period (Grodecki et al., 1978). Thus, the results from Beauvais should be viewed as an upper limit to the potential lighting provided by grisaille-type windows.

The results indicate again that the vaults above windows receiving direct solar radiation are particularly strongly lit compared to Le Mans, which receives a more even illumination across the choir vaults. The upper vaults are slightly better illuminated (12-13 cd/m^2 excluding the bright streaks adjacent to the windows) than at Le Mans (8 cd/m^2). This difference between the two is not substantial considering that vault luminances in the upper portion (western choir vaults) of the Beauvais profile are equivalent to those in Le Mans. Cloudy weather improvements in vault luminances seen for grisaille programs are much greater, such as seen in comparing Cologne and Tours (Figure 4.17 below). In addition, the upper triforium tracery and north choir pillars receiving direct sunlight represent a region of high illumination, much greater than that seen (except in isolated patches) for Le Mans. However, similar to observations in the St-Serevin example, the upper triforium spandrels in the hemicycle and on the south choir possess luminances closer to 10-14 cd/m^2, which is essentially equivalent to that of Le Mans's corresponding choir arcade (7-12 cd/m^2). Additionally, the choir arcade in Beauvais is as dark or darker than that of Le Mans, even on the north side with the exception of only a few arches illuminated more directly by sunlight. Thus, again it can be concluded that improvements to the illumination of forms under sunlight (relative to sunny full-colour interiors) is largely restricted

to those regions receiving direct solar radiation rather than a uniform improvement across the interior. This is because Le Mans appears to have a more uniformly-distributed illumination under sunny conditions, whereas in Beauvais and St-Serevin the illumination profile is more steeply graded according to the position of the sun.

This is further confirmed for a summer profile of Beauvais's cathedral vaults (taken in the choir), presented in Figure 4.15c (partly cloudy conditions with solar disk fully exposed, 1400 GMT on 16 June, 2008) and 4.15d (mostly cloudy conditions with sun completely obscured by stratocumulus overcast, 1406 GMT). The transition from sunny to cloudy conditions was associated with an illuminance decrease from 34 lux to 26 lux (Instrument 4) in the direction of the camera lens. Between the two scenarios, the lighting on the tracery on the south side of the cathedral remained virtually unchanged (only slightly darker, quantifying the magnitude of the internal reflections from direct solar radiation). The elevated vault rib luminances adjacent to windows are also only slightly (20%) lower for the cloudy example in the hemicycle. The most profound changes are in interior vaults, which essentially decrease by half going into cloudy conditions, and the north side of the hemicycle, which exhibits greater darkening (a third of the sunny luminances). Thus, clearly within a white-dominated interior sunny conditions do not provide strongly increased illumination for much of the cathedral's surfaces as compared to cloud cover daylighting, except for surfaces on the side of the cathedral receiving direct sunlight.

Furthermore, the winter examples cited above likely provide the greatest discrepancies between sunny luminance profiles in full colour versus white dominated interiors. One of the best summer solar lighting comparisons between the two types of interiors is provided by the examples of Évreux and Le Mans around midday. Both cathedrals receive the greatest direct sunlight at the surface near the altar (in the eastern choir) during this time, but they have different orientations (Le Mans to the south-southeast and Évreux due east). As such, the Évreux example has a greater number of directly sunlit windows than Le Mans at the time of measurements. Figure 4.16a and 4.16b show typical luminances from sunny conditions in the early afternoon in Évreux Cathedral. At the clerestory level, the actual luminance levels do not appear to differ substantially than Le Mans's interior (Figure 4.10d). The vault luminances in both interiors are between 10-15 cd/m, with Le Mans's values skewed only slightly lower than Évreux's. The spandrel luminances on the side of the cathedral receiving solar radiation are

actually lower in Évreux's example than for Le Mans. Évreux does, however, demonstrated brighter points than Le Mans on the side of the cathedral facing clerestories with direct sunshine (compare Figures 4.16a, 4.16c, and 4.10d). In Évreux, pillars at the clerestory level have streaks of luminance averaging 30 cd/m^2, whereas in Le Mans similar streaks average 20 cd/m^2. In Évreux, the spandrels below the triforium average just above 40 cd/m^2, whereas in Le Mans the choir spandrels are correspondingly lower, at around 25 cd/m^2. Similarly, at the lower levels the 20-30 cd/m^2 received at the column bases in Le Mans becomes 30-40 cd/m^2 in Évreux. Thus, as far as the summer solar illumination of architectural forms is concerned, the greatest improvement between full colour and grisailled interiors appears to be just under half for some surfaces in the lower choir opposite the sunlit windows and less than that for other areas.

Therefore, solar illumination does not appear to provide substantially more light to decorated surfaces in the Late Gothic example as compared to the coloured Rayonnant interior. While it is clear that the lower elevations and the more transmissive windows of most Late Gothic structures provide an increase in ambient illuminance under sunny conditions, the actual lighting of many architectural surfaces does not improve between the two types of aesthetic. The contrast between windows and their tracery may increase for higher translucency glazing, accentuating these forms in some cases. However, the grisaille revolution programs (Cologne Cathedral) often employed relatively simple tracery designs, and complex Flamboyant tracery was frequently decorated with more coloured glass (Troyes Cathedral) than the apertures at the beginning of the fourteenth century. Therefore, the scope of the formalist argument appears to be limited, at least for sunny conditions in Rayonnant interiors, where the thirteenth century coloured tradition and the glass of later centuries seems to perform similarly in highlighting several architectural forms.

However, for overcast conditions the formalist argument appears to have greater merit. A cloudy weather luminance map is unfortunately not available for Le Mans, but with similar daylight factors found in the inner choir of Tours, we can probably expect comparable lighting performances and vault luminances between the two interiors. A collection of three choirs for which exterior horizontal illuminances (indicated in parentheses) were similar at the time of observations are represented here (Figure 4.17): Tours (8610 lux), St-Ouen (7540 lux), and Cologne (9600 lux). Overcast, foggy exterior conditions dominated the measurements for Tours and St-Ouen, whereas Cologne saw a general stratus overcast without fog. Although Cologne,

unlike St-Ouen and Tours, possesses painted vaults, the reflectance of the white paint was corrected to represent that of the interior's limestone by downward calibrating pixels associated with the white paint by 76.4% of the original value.

The effects of the whiter glass on the illumination of the architecture appear to be quite significant, especially for the well-preserved grisailles of Cologne, which illuminate the vaults over 5 cd/m^2. By contrast, the vaults of Tours Cathedral are illuminated predominately under 1 cd/m^2 outside of the presence of the two band windows in the choir. The anomalously bright patch on the vaults near Tours' cathedral choir is associated with Window 105, which has modern replacement glass in its upper levels (Grodecki et al., 1981). More modern glass is present in the clerestory of St-Ouen than in the other two examples, but many of the windows behave in a manner comparable to the original glass. For example, Window 240 (to the right or south of the central axis window) retains almost all of its medieval glass, and it produces a luminance profile on the adjacent vaults that is equivalent to those of the other windows. In St-Ouen, the vaults ribs receive the greatest illumination and contrast strongly with their surroundings. In addition, the overcast sky provides more symmetric, even lighting of these ribs, enhancing their contrast with their surrounding architecture and accentuating their form. The contrast of lighting between different forms appears to be less significant in Tours under cloudy conditions and Le Mans under sunny conditions, which produce a more even illumination of the architecture. Thus, glaziers and architects appear to have used not just greater illumination but illumination contrasts to accentuate forms. Also in St-Ouen, the inner vaults receive an even luminance between 1.5 and 2.5 cd/m^2, more than double those of the vaults in the inner choir of Tours.

Other important features, such as triforium tracery, also demonstrate notable luminance differences between the grisailled and full-colour interiors. For example, while in Tours the contamination lighting from the nave is visible along the edges of the image, deep inside the choir the luminances of the spandrels at the triforium level remain close to 1 cd/m^2, whereas those on the corresponding triforium panels and nearby stone tracery of Cologne and St-Ouen approach 2-3 cd/m^2. These higher values seen in the grisailled interiors are consistent with the illumination on the foliage decoration in the case of the Le Mans triforium under sunny conditions. The lower spandrels above the choir are also brighter in Cologne and St-Ouen as compared to Tours as well, and the piers breaking the lancets have significantly higher

luminances near 3-4 cd/m^2 (Cologne and St-Ouen) compared to the 1.5 cd/m^2 (Tours). Thus, for these white-dominated interiors, the illumination of important forms such as the vaulting and triforium tracery appears to be markedly greater for cloudy conditions than for full-colour interiors. In fact, the grisailled programs provide two or more times greater luminance values to architectural features than the fully coloured glazing, and more evenly over the surfaces than the gains over programs associated with sunlight in St-Serevin. In addition, the cloud cover conditions produce luminances at or below those of full-colour interiors under clear sky conditions.

The St-Serevin cloudy day measurements, taken when there was a substantially greater horizontal exterior illuminance of 14000 lux (with slight brightening toward the sun associated with a mid-level, undulating altostratus overcast), are presented in Figure 4.18a. A residue is present on the walls and vaults in some areas, and one sample in the north nave gave an average stone reflectance of 34%, substantially lower than the 45-55% seen in most interiors. Due to this and the more cavernous nature of the vaults, the vault interior is actually darker than that of Tours Cathedral under cloud cover, and this is true as well for the hemicycle vaulting. However, the contrast between the darker arch of the vaults and the ribs near the windows is greater, as demonstrated for the other Late Gothic examples (St-Ouen) above. Also, the triforium tracery and spandrels receive significantly greater light than at Tours (Figure 4.19), which retains 1.5 cd/m^2 on the side walls where St-Serevin received 4-6 cd/m^2 (likely 2.3-3.5 cd/m^2 if provided with the same horizontal exterior illuminances as at Tours). In addition, unlike for sunny conditions, where this increased illumination relative to the full-colour interior was patchy and largely on the surfaces opposite to the windows receiving direct sunshine, cloud cover provides a more evenly distributed increase in illuminance at the triforium level across both the north and south sides of St-Serevin. Therefore, the illumination of Late Gothic triforium and vault ribs is consistent, with patchy increased illumination during sunny periods for some surfaces compared to full-colour interiors, but broad increased illuminances over most surfaces during cloudy periods. Thus, for the complex triforium tracery in St-Serevin and Beauvais, the formalist argument appears to be as much or more applicable for overcast skies than for sunny conditions.

St-Serevin is also a markedly coloured program and as such represents one of the darkest of the examples of the Renaissance interiors (and thus the strictest threshold of comparison with full-colour programs), as further discussed in Section 4.3.2. When comparing St-Serevin with

cathedrals that incorporate markedly more white glass, the increase in luminance of various forms is substantial. In Figure. 4.18b, choir luminances are shown for a horizontal exterior illuminance estimated as 16800 lux, slighly greater than the 14000 lux exterior horizontal illuminance during the St-Serevin profile. Other important considerations are St-Serevin's smaller size, which would support a greater concentration of light and thus higher values than for the broader interior of Évreux, and its darker limestone reflectance (34%), which would have the opposite effect. The interior of Évreux is clearly much brighter, with spandrel luminances below the triforium of 5-8 cd/m^2, deep vault and triforium tracery luminances between 2-4 cd/m^2, and rib/vault luminances adjacent to windows between 8-13 cd/m^2. Even if these values were to be divided in half to account for the difference in exterior horizontal illuminance with Tours, they would still be two to five times greater than luminances under cloudy conditions in this particular full colour interior.

A contrast between sunny and cloudy conditions in the two types of cathedrals also provides interesting results. Comparing the sunlit full-colour interior of Le Mans (Figure 4.14) with the overcast illumination in Tours, Cologne, Évreux, and St-Ouen demonstrates that the formalist argument cannot be applied to comparisons between sunny and cloudy conditions. It is clear that sunlight in Le Mans produces much greater lighting, of forms and the broader interior, than any grisaille revolution program under most cloudy conditions. This provides an important restriction on the formalist argument, demonstrating that full-colour interiors are able to supply an even, high illumination of forms and that grisailles do not provide a universal improvement in lighting across all weather conditions compared to coloured programs. A decrease in the amount of sunlight for the illumination of coloured interiors, however, might have promoted the use of whiter glass for its ability to provide much greater luminances than coloured interiors under cloudy conditions.

It also appears that, while some gains are afforded in vault and triforium illumination in interiors such as St-Serevin and Beauvais under sunny conditions compared to thirteenth century full-colour interiors, the improvements for cloudy conditions are often greater as well as more even and symmetric across the interior (due to the symmetrical luminance distribution of the standard overcast sky). Therefore, we conclude that the formalist argument is valid, but with important caveats: grisaille and white glazing does not provide a universal increase in illumination for all weather conditions. Thus, only an increasing awareness of overcast lighting

would have anticipated substantial lighting gains for most of the interior associated with white glass.

4.2.3 The Effects of Backlighting on Grisailled Interiors under Sunny Conditions

In general, the grisaille revolution provided a universal shift to higher lighting values across both cloudy and sunny conditions. For example, during overcast conditions grisailles allow an increase in the ambient illumination (seen in daylight factors) and luminances on architectural forms compared to colour-dominated interiors. In addition, sunny post-grisaille revolution interiors have generally higher ambient lighting than full-colour interiors under sunny conditions, and they also provide unequally higher illumination of some architectural forms compared to coloured programs. Therefore, the increase in white glass appears to be a reasonable compromise between the two types of skies from the formalist viewpoint, giving greater illumination to some areas under sunny conditions and to most parts of the cathedral under cloudy conditions than coloured Rayonnant programs.

However, backlighting is another factor that should be taken into account when considering the effectiveness of white-dominated versus coloured glass under sunny illumination. Sowers (1965) argued that the grisaille revolution was perhaps motivated by a concern for backlighting, defined as a visible blackening (or in some cases an extreme whitening associated with patches of direct sunshine) on windows receiving markedly less daylight illumination than those opposite them. Backlighting thus occurs when internally transmitted and reflected light on the window surface exceeds window transmission, obscuring the windows facing those that are receiving greater illumination. Such lighting, if too extreme, renders them aesthetically ineffective and illegible if not repulsive. By definition, backlighting could not be a viable concern if the assumed background exterior illumination pattern is a standard overcast sky, in which all directions (and all windows) receive roughly the same illumination. Even for variations of the overcast sky, where one direction is slightly brighter than another, backlighting would not obscure opposite windows to any visible degree.

From the above discussion, backlighting is primarily a solar lighting concern. When addressing this factor, Sowers (1965) emphasizes the inequity between the light admitted and received in the glass cage aesthetic of Rayonnant interiors during sunny conditions, and he uses Ste-Chapelle on the Île-de-la-Cité in Paris as a primary example. In particular, the tall and narrow chapel receives (at most times of a sunny day) much greater illumination on its south

side, which completely obscures (blackens) the stained glass of the north wall, making it illegible and unattractive, during most seasons. Sowers consequently argued that equalizing the light in the interior was made possible by converting to grisaille programs. However, this conclusion can only be made assuming that north-facing windows were converted to grisailles while south facing windows maintained the full-colour tradition. While true for the scattered, strategically-located, north-facing grisailles used in early thirteenth century colour-dominated programs, this is clearly not the outcome of the grisaille revolution, which applied large quantities of grisaille glass on all sides of the cathedral. In addition, most cathedral choir clerestories do not maintain a height-to-width ratio as extreme as that of St-Chapelle. For example, Ste-Chapelle's width is 10 m and the height of the lateral windows are 15 m high by 4.65 m wide (with very little in the way of wall space between the lancets); by contrast Le Mans has a slightly greater choir width of 12 m and shorter windows (9 m high by 5.5 m wide). Therefore, the backlighting seen in the royal chapel would inevitably be more extreme than for most interiors, especially given the height of the windows and their close proximity to each other. Furthermore, Ste-Chapelle is a small, compact interior (the clerestory windows begin close to the floor level), causing the backlighting to receive substantial contributions from internal reflections of sunlight (rather than just direct sunlight) in the contained interior compared to a vaster, more open cathedral environment. Therefore, our study also includes a series of observations on backlighting in full-colour and grisaille-dominated cathedral interiors during different seasons.

Our observations suggest that backlighting is much more of a handicap to the legibility of the iconographical program for interiors with apertures containing grisaille-dominated glass than for Rayonnant full-colour programs. In addition, given the low solar angles of winter (and the greater amount and higher elevation of the bright patches of transmitted direct solar radiation), we would expect backlighting to be much more extreme during the winter compared to the summer, although summer backlighting on the order of that seen during the winter would still be prominent in the hours after sunrise and before sunset. However, even during the late morning, spring and summer backlighting can be particularly detrimental to the aesthetics of the glazing, such as observed for Cologne at 812 GMT (30 April, 2007) (see Figure 4.20). During the winter, given persistently low solar angles and the restriction of the sun to the southern half of the sky, we can expect a similar degree of backlighting of Cologne's choir throughout much

of the day. This is confirmed by analyzing the effects of backlighting on the grisaille-dominated programs in the winter for Beauvais Cathedral (see Figure 4.21). We note that Figure 4.21a was taken when the strongest solar illumination was admitted by the two best-preserved medieval grisaille windows in the southern choir hemicycle. In this example, backlighting is particularly prominent on the figural glass, which transmits much less light than the surrounding grisailles, causing backlighting to be more severe over the bands. Only during the relatively brief part of the day when the sun is directly aligned with the choir axis would the backlighting be minimized.

We thus conclude that the iconographical focal-points, i.e. the standing saints, of most band window programs appear to be more susceptible to the adverse effects of backlighting when provided with solar illumination. This also appears to be the case in St-Ouen (Figure 4.22), where the unpierced triforium appears to receive the greatest illumination from the northern clerestory windows (most nave clerestories date largely from the late fourteenth and early fifteenth centuries). However, it is also clear that backlighting causes the north clerestory windows to be partially or fully obscured in large, bright white patches of enhanced illumination. The same effects (not documented) were also observed earlier in the afternoon in the north choir clerestory windows. Therefore, clearly under sunny conditions grisaille windows, throughout much of the day during the winter, and throughout the morning and evening during the summer, produce significant backlight that destroys the aesthetic and iconographical function of windows opposite those experiencing direct illumination from the solar disk. Further evidence of the sensitivity of post-grisaille revolution interiors to backlighting was also observed in Troyes Cathedral, where a marked fading of the north windows (not shown) were observed around 1030 GMT (19 June, 2008) under partly cloudy skies with a partially-veiled (by cirrus/cirrocumulus) sun. Thus, during the winter midday much more obscuration could be expected. Slight fading was observed in Évreux during a clear summer midday (1221 GMT, 24 June, 2008), suggesting similarly that winter backlighting is likely as or more extreme than for Beauvais (which at 1211 GMT on 16 June, 2008, for a partly cloudy day with cumulus clouds in the south and west and sun fully exposed, showed little indication of fading despite demonstrating heavy winter backlighting).

By contrast, under the same summer morning and winter solar angles backlighting in earlier thirteenth century interiors does not , according to our observations, appear to be a

particularly important concern for most of the window space and at most times of day in any season. In order to provide a valid comparison with the largely Rayonnant interiors discussed above, Le Mans was used as a relevant example for full-colour programs. Le Mans's clerestory windows are shorter by about 6-9 m than those of Cologne and Beauvais, but the two grisailled choirs are also wider (closer to 15 m). During the summer midday in Le Mans (Figure 4.23b), as expected, there is no obvious backlighting over clerestory windows opposite those experiencing direct sunlight. Given midday solar illumination, the greatest interior illumination should be near ground-level in the choir, thus reducing the risk of backlighting on all relevant windows. However, with the same windows sunlit during the winter (Figure 4.23c), strong backlighting is visible on the walls and choir piers but appears to have little influence on the legibility of the windows. The same pattern, that of a brighter wall space but no evident obscuration of the windows, is seen for the summer morning photograph taken in Figure 4.23a. In the winter afternoon (Figure 4.23d), it is clear that a few north choir clerestory windows receive some dulling associated with backlighting, most visible in the upper right corner of the image. However, even in this case most of the windows are still clear and highly legible, with only very isolated patches of brighter light (presumably associated with white glass) producing any notable obscuration on the opposite windows.

On the summer morning of 30 June, 2008 (700-800 GMT), the clerestory windows of Le Mans Cathedral exhibit backlighting to a somewhat greater degree than in the previous examples, although still not to an extent to render the windows illegible. A luminance profile quantifying some of this backlighting is provided in Figure 24. The easily legible lancets in Window 206 and Window 208 have luminances between 25-50 cd/m^2, whereas strongly obscured regions average 70+ cd/m^2, with the greatest (white) obscuration on Window 208 clearly receiving as much as 150 cd/m^2. Any areas above 45 cd/m^2 (bright green and brighter colours on the luminance profile) may also experience some backlighting, especially when superimposed over darker colours. However, as is clearly evident, these regions are sporadic and confined to the bottom of the windows; they do not detract from the legibility of the broader figure that fills multiple registers of each lancet. Early mornings, either in the winter and summer, likely bring more backlighting to the windows of Le Mans, but these periods would be relatively short lived, and the cathedral's choir clearly does not demonstrate the mid-late morning backlighting and high levels of afternoon winter backlighting as demonstrated in the

white-dominated programs at Cologne and Beauvais. Therefore, the reduced translucency of the full-colour windows appears to be associated with a perfect balance under sunny conditions; such windows provide a more even, elevated luminance profile in the interior while at the same time do not admit so much light as to produce broad, obscuring backlighting on the north windows.

To summarize, our observations suggest that grisailles, and the general prevalence of white glass in windows that receive direct solar radiation, produce much greater backlighting compared to coloured windows. Early thirteenth century programs, with their tactical placements of grisailles on north-facing surfaces and/or in crevices, appear to have worked to reduce or eliminate the effects of backlighting. This suggests that early Gothic design achieved a high level of sophistication surrounding the balance of interior lighting, and with respect to backlighting thirteenth century glazing strategies appear to have been developed with an assumed exterior direct solar illumination. However, the white-dominated or high translucency windows of grisaille revolution and later programs significantly obscure the windows opposite those receiving direct solar radiation, even in interiors with shorter windows such as St-Serevin and St-Ouen. In particular, the coloured glass of visual interest within the band windows is rendered especially obsolete. Our findings thus disagree with Sowers (1965), who suggested that grisailles solved the problem of backlighting rather than accentuating it as we discovered. With limited gains in form illumination, accompanied by the major drawbacks associated with intense backlighting, we would argue that Gothic stained glass programs from the grisaille revolution and after were possibly executed with the assumption that a cloudy illumination pattern would prevail, as they appear to best maximize lighting under these conditions.

4.2.4 The Ambulatory of Chartres: The Incorporation of Later Grisailles into a Full-Colour Program

The ambulatory of Chartres Cathedral, while once nearly completely glazed with coloured windows, today holds a large number of grisailles from the late thirteenth and fourteenth centuries (along with white glass from the Renaissance period). Because Chartres's ambulatory retains many of its original full-colour windows, interrupted only intermittently with grisailles, it provides an excellent case study on the effects of isolated white-dominated windows on broader ambulatory illumination. Additionally, aisle-level windows were likely meant to provide the dominant source of lighting in the ambulatory, as the choir clerestory contributes little to the ambulatory illumination given the height of the present choir screen. In our

measurements, this was further reinforced by the current blackened state of the high windows (and also with the consideration that Windows 103, 104, 105, and 106 (see Figure 4.25) were covered at the time of observations).

The ambulatory windows containing grisaille or quarry/white glass are labeled in the Figures 4.26 below and are discussed thoroughly in Lillich (1972) and Grodecki and Perrot (1981). The oldest grisaille (1235-1240), congruent with the strapwork of the glass in adjacent apertures (and thus probably oriented as it was originally), is provided by Window 19 (Lillich, 1972; Grodecki et al., 1981). Located in a north-facing aperture oriented toward a slight crevice between two ambulatory chapels, this window appears to conform to the logic of grisaille placement in early gothic programs (discussed above) as seen in Troyes Cathedral (Pastan, 1994). However, the chapel is three-sided and much shallower (but no less wide) than the other prominent five-sided radiating chapels, thus exposing the window to greater exterior illumination than for other, more obstructed crevice-type grisailles in Chartres ambulatory. In addition, its orientation prevents the obscuring effects of backlighting on other windows. Thus, it may have served a secondary purpose, perhaps also to provide more illumination to the north side of the choir screen (containing a figural frieze) that was constructed during the same time period (1230-1240) as this window (see Jung, 2000). This is particularly plausible considering Window 19's closer proximity and more perpendicular orientation to the choir screen compared to most radiating chapel windows.

Windows 25 and 27 are the next oldest and are believed to have replaced earlier coloured windows between 1259-1270 (Lillich, 1972). Therefore, they appear to predate or date contemporaneously to the construction of the sacristry (last third of thirteenth century or early fourteenth century), although another tall, obstructing wooden structure may have been present on this site since the beginning of the thirteenth century (Lillich, 1972). Thus, if not to account for a decrease in exterior illumination associated with the construction of the sacristry, these grisailles may simply represent a desire to increase lighting compared to that admitted by the original coloured windows. Windows 3 and 10 date from the end of the thirteenth century, before the construction of the now-obscuring Chapelle St-Piat (built in the fourteenth century to the southeast). In its original state, solar daylighting during the morning would have countered the increased illumination from the grisaille glass in Window 3 to prevent backlighting, but today even diffuse lighting will cause backlighting in the apse chapel due to decreased

transmittance from the south associated with the adjacency of the auxiliary chapel. Therefore, these windows appear to have been added without regard to the current chapel simply to permit more light into the building, a fulfillment of Rayonnant tastes (Lillich, 1972).

Also in the south ambulatory, the small grisaille Window 6 appears to date from the mid-fourteenth century, as does most of Window 26 (two lancets) (Grodecki and Brisac, 1985). Windows 22 and 24, two separate, white-dominated single lancets, date largely from the end of the sixteenth century, with some twentieth century additions (Grodecki and Brisac, 1985). These were perhaps installed to shed more light on the contemporary Renaissance sculpture of the choir screen, although this only seems reasonable if prevailing cloud cover or diffuse lighting was a predominant concern (especially given the fact that Window 26 was already in place to provide increased lighting to the choir screen), given the high illuminances in the Bourges's ambulatory sunny measurements. However, similar Renaissance windows were not provided to the south ambulatory choir screen. Both sides (north and south) of the ambulatory have roughly the same number (6) of white-dominated lancets. Thus, with this in mind, it appears that the north ambulatory best represents the effects of thirteenth century grisailles (in their more traditional role) on the interior lighting, whereas the south ambulatory best demonstrates fourteenth century and later adjustments to the original program.

In the same way as done in the nave, two rounds of daylight factor measurements were taken in the interior of Chartres ambulatory. Where two daylight factor measurements are provided for a specific point, daylight factors were averaged (and the averages in the north ambulatory are, for the most part, highly precise). In the south ambulatory, however, we only performed one round of measurements for each location, and the results from the two separate series of observations are thus separated. The second round (Figure 4.26c), analyzing points between column pillars in the ambulatory passages, was completed rapidly (largely within three minutes) and thus are probably more representative of lighting under relatively constant horizontal exterior illuminances (as such they represent relatively stable values). Precise average measurements, or daylight factors represented by only one round of measurements, are indicated in the figures by black shading and light pink shading respectively.

The results indicate that only a few grisailles, such as those in the north ambulatory, can provide above-average illumination across a relatively broad area. For example, readings in architectural bays adjacent to the north transept, in the immediate presence of full-colour

windows, are consistent with daylight factor estimations from the ambulatory at Bourges. However, even the largely obstructed Windows 25 and 27 provide an environment of increased illumination (daylight factors between 0.06% and 0.07% in the inner ambulatory). Outer and inner ambulatory measurements peak for the largely unobstructed grisaille from Window 19, the oldest of the white glazing. Then daylight factors appear to decrease toward the westernmost five-sided radiating chapel of the north ambulatory before rebounding again quickly in the presence of Window 3 and the more transmissive white windows of the south ambulatory. Thus, the north ambulatory possesses only a few darker areas that are perhaps more representative of full-colour lighting, whereas essentially three or four grisaille windows provide elevated daylight factors for concentrated areas of the north ambulatory.

As expected from previous measurements on the effects of the grisaille revolution, the windows almost double the ambient lighting in the interior of the inner ambulatory and more than doubles it in the outer ambulatory. In this case the formalist argument can barely be said to apply, as the vaulting, tracery, and decoration of the north ambulatory and choir were completed during the High Gothic period and never conformed to the Rayonnant aesthetic, even if new windows did. Sherrill (1924) claims that the inclusion of more grisailles in Chartres's ambulatory, and the replacement of its earlier precious windows, was born out of a desire for more light because officials had realized the mistake of having too much colour in a relatively cloudy climate. As a modification of this argument, we would maintain that the new desire for more light toward the end of the thirteenth century, as it manifests itself in Chartres, transcends formalist concerns and suggests that there was a real need to provide more interior illumination to the cathedral. This, in turn, might be readily associated with a greater awareness of interior lighting during overcast conditions, especially given the likelihood that preexisting full-colour windows were likely present in the apertures before they were replaced by grisailles.

The effects of the inclusion of white glass in the facade are more dramatic in the south ambulatory (Figure 4.26b and 4.26c), where there are more grisaille-type windows from the late thirteenth and fourteenth century. First, near the apse chapel, the single bulged quarry grisaille in Window 3 appears to provide much greater lighting in the chapel itself and in the adjacent outer ambulatory architectural bay. In fact, the daylight factors are over double those of the brightest chapels in the ambulatory of Bourges Cathedral, which are smaller and would normally provide more concentrated lighting than Chartres's broader chapels. Thus, this single grisaille window

establishes the apse chapel as one of the brightest locations in the ambulatory, with lighting levels closer to those expected in Renaissance interiors (see Section 4.3), despite the blocking of light from the south associated with the passageway of the Chapelle St-Piat. The greater daylight factor in the chapel may also speak to the window's greater translucency compared to the older Window 40. However, measurements to the south reveal that the white glass contained in a few apertures provides anomalously high lighting (compared to most full-colour interiors, such as Bourges ambulatory) across much of the south ambulatory of Chartres. Daylight factors exceed 0.1% for nearly all points east of the zodiac window in both rounds of measurements, with locally higher values concentrated near Windows 22, 24 and 26 ranging between 0.1% and 0.35%. Of all the grisailles, Window 26 appears to provide the greatest illumination in the inner and outer ambulatory passages, even more than the two largely Renaissance and modern lancets to the east. The measurements shown in Figure 4.26c gives a particularly coherent view of the diffusion of light in a grisaille-dominated interior, and it indicates that above-normal illumination extends from the apse chapel to the south transept, with daylight factors returning to values more typical of full-colour interiors on the edge of the ambulatory (i.e., adjacent to Window 30).

Therefore, it appears that the largely thirteenth century grisailles of the north ambulatory provide strategic, focused regions of higher illumination (just under double the average full-colour lighting) and compensate for obstructions (Windows 27 and 29). By contrast, the fourteenth century and later glazing provides much broader regions of significantly greater illumination than seen for full-colour programs. In fact, some locations in the south ambulatory have daylight factors that are nearly an order of magnitude greater than values obtained for coloured programs. Thus, clearly by the fourteenth century and thereafter, a very substantial increase in lighting is associated with the replacement of coloured windows with white-dominated glass. Also, there is a much greater increase in ambient illumination than would be seen for the deliberate placement of grisailles in early Gothic programs (for which Chartres's north ambulatory is somewhat more representative). This new glass was incorporated into the ambulatory in spite of the fact that full-colour windows had already been produced at great expense to fill these apertures. This suggests that church officials strongly desired to change the quality of interior lighting, especially by the end of the thirteenth century. As the whiter glazing clearly provides a substantial lighting improvement under overcast conditions, its incorporation

may be in part a reflection of concessions to an increasingly cloudy climate, for which direct sunlight was perceived as less frequently available to the south ambulatory apertures.

4.3 Late Gothic Interiors: The Fourteenth through Sixteenth Century

The aesthetics of the fourteenth century brought a permanent end to the richly coloured, mosaic glazing formula in northern Europe, starting first in France and eventually in Germany. French glazing during the second half of the fourteenth century and much of the fifteenth century suffered because of a halt in major construction projects during the Hundred Years War and the catastrophic disasters (plague, famine, civil strife, etc.) of that century. However, a few major glazing programs continued in France even through these hardships (for example, St-Ouen in Rouen and Bourges Cathedral) as well as in other parts of Europe (The Low Countries, England, and Germany). Evidence from Sées Cathedral, Évreux Cathedral, and La Trinité at Vendôme indicate that the transition to white-dominated windows was complete by the early fourteenth century, preceding the development of yellow stain, its first documented use in France being in 1311 (Lillich, 1994). After the Hundred Years War, the glazing tradition returned to France in full force, gradually adopting the colourful, richly detailed narrative cycles that were more common during what we refer to generally in this text as the Renaissance period in stained glass.

4.3.1 Évreux Ambulatory and Choir: The Grisaille-Dominated Interior

While the ambulatory of Chartres provides an indication of how just a few grisaille windows affect the illumination of the interior, the remarkably well-preserved glazing at Évreux indicates the range of illumination possible when a Rayonnant structure possesses a large quantity of white medieval glass. In fact, the interior of Évreux (see Figure 4.27) perhaps provides the best representation of a cathedral glazed during the fourteenth and fifteenth century available today in Europe. Furthermore, royal attention made it one of the more lavish projects of its time. Most of the western ambulatory windows (21-27), and many of the radiating chapel windows (9-14, 16, 18 and 20) date largely from the glazing campaign of the first third of the fourteenth century. Also, many of the clerestory windows (especially those in the hemicycle in addition to windows 207, 211, and 212) also date from the same time period. A few more windows were also installed in the second half of the fourteenth century (windows 15, 17, and 19 in the north ambulatory radiating chapel, and Window 208 in the clerestory) or at the turn of the next century (windows 203, 205, 210, and 214). From the Renaissance, the narrower triforium windows of the choir contain glass dating largely from the fifteenth century and early

sixteenth century, and at the aisle level the windows of the contemporary Lady Chapel (0-8) were glazed between 1467 and 1469. Thus, while early fourteenth century windows are the dominant light sources for many of our interior measurements in the ambulatory, Évreux affords a remarkable assemblage of medieval glass from both the (later) Rayonnant and Late Gothic periods, an era we generally associate with potentially increased cloud cover.

The measurements were taken on a cloudy summer day during a period of scattered light rain (nimbostratus) in the spring of 2007 and twice under stratocumulus overcast in the summer of 2008, and two rounds of vertical measurements were taken but only round is presented in Figure 4.28. Unlike in Chartres and Strasbourg, virtually no artificial lighting was present at the time of measurements, and thus subtraction was not required. The exterior location (Place Charles de Gaulle) selected for the spring 2007 round of measurements, given the limitations of the instruments, likely provides a representative horizontal illuminance near the cathedral (being much more open than the restrictive west-front sky views in Angers and Tours, which capture 90% of the hemispherical horizontal illuminance). This argument was confirmed for a verification experiment with overcast and mostly cloudy conditions brightening toward the sun in June, 2008, in which the horizontal illuminances at Place Charles de Gaulle and a location with a hemispherical sky view (pedestrian bridge/roof overlooking the train tracks near Gare Évreux) were approximately equal. The LI-COR-Instrument 2 conversion formula (Appendix II) was used to calculate exterior illuminances for the first round of observations. In the interior, few contaminations are present at any given location, although an important background consideration is the fact that much of the cathedral was destroyed during World War II and was rebuilt thereafter. The stonework, however, is clean and was proven to have reflectances typical of other cathedrals, with three diverse samples (with little variance in the results) in the nave and choir averaging a reflectance 54%. Similarly, few modern exterior obstructions are present (with the exception of relatively low-rise buildings across the street from the north side of the ambulatory). Thus, given these considerations, the results from Évreux we believe are strongly representative of the original lighting of the cathedral. We can contrast these with estimated daylight factors in the Rayonnant ambulatory of Amiens, which possesses large, modern glazed aisle windows and estimated daylight factors (not shown) primarily between 0.8-1%.

In general, the highly precise results (Figure 4.28) indicate that the well-preserved, heavily white-dominated glazing of Évreux provides daylight factors in the ambulatory ranging

largely between 0.15% and 0.31% and the choir averaging slightly lower with daylight factors between 0.08% and 0.20%. Therefore, the ambulatory appears to be broadly brighter than most points in the choir due to the closer proximity of low-elevation windows and the lower height of the vaults over which internal reflections occur. The centre of the choir also appears to be the area of greatest choir ambient illumination, as discussed for Chartres's nave in Section 4.1.1. In the eastern choir, values between 0.11-0.18% are furthermore several times greater than the 0.03%-0.04% HDFs determined for corresponding locations in the choirs of Le Mans and Tours. In fact, the daylight factor values throughout much of the interior are a very large departure from those calculated for full-colour programs, which often only reached values of 0.02%-0.05%. *Thus, for several points the interior illumination in Évreux had increased by an order of magnitude compared to interiors such as Bourges.* Also quite notable is the hemicycle effect seen in the elongated Lady Chapel, which contains a large proportion of fifteenth century, more richly coloured glass. The illuminances, as if simulating the effects of a mini-hemicycle, increase toward the semi-polygonal arc at the east end of the chapel from a minimum daylight factor of 0.06% just inside the entrance to the chapel (bordered by no nearby windows) to 0.38% under the vault convergence near the Notre Dame sculpture. In terms of the physical values, however, equivalent or higher daylight factors were actually obtained for several ambulatory locations located further from the nearest apertures, suggesting that the coloured Renaissance windows provide somewhat less illumination that the whiter glass of the ambulatory. These results are further confirmed for the vertical daylight factors, which are lower inside the Renaissance chapel than for some regions of the ambulatory. In addition, the vertical daylight factors in the western architectural bays of the north and south ambulatory (where, in the latter case, the aisle-windows are largely obstructed on the exterior) confirm that the clerestory and triforium windows make a significant contribution to the daylight factors in the ambulatory. In particular, for these areas VDFs are greater facing the choir than toward the ambulatory windows.

In general, the results from Évreux provide a very well-preserved example of a cathedral ambulatory interior dominated by grisaille apertures. The values obtained are similar to those seen in Chartres's south ambulatory, but are higher and extend across a broader area. They are also well under an order of magnitude smaller than from the maximum lighting (a daylight factor around 1%) expected from measurements in Amiens. Therefore, the contrast between the post-grisaille revolution illumination from programs developed only a century earlier appears to be

quite extraordinary. Furthermore, the later Renaissance glass added to the interior proved to be somewhat less tranmissive than the grisaille band windows, creating an environment of lower ambient illumination, but it remains elevated well above thirteenth century glass. Thus, it seems possible to conclude that virtually all post-grisaille revolution programs belonged to an aesthetic tradition that affords a radical and decisive break from twelfth and thirteenth century norms.

4.3.2 The City Church: St-Serevin in Paris, St-Pantaléon in Troyes, and St-Nicolas in Troyes

The city church of St-Serevin in Paris is notable for the medieval glass of its nave and choir, which also dates largely to the fourteenth and fifteenth centuries, although a newfound love of colour also takes on a more important role in the glazing of St-Serevin as compared to Évreux. Virtually all windows of the choir and eastern nave regions date from the second half of the fifteenth century, with the exception of Window 206 (see Figure 4.30a for window numbers), produced during the seventeenth century. Despite the overall good state of preservation of the glass at the time of measurements, a variety of modern contaminations are present. The triforium-level windows, while short, contain richly coloured modern windows, and the late fourteenth century windows (Windows 215-220) are heavily restored. In addition, there is some modern glazing in the fifteenth century windows, most notably in the tympanums of Windows 204, 211, 212 and 213 (but otherwise these windows retain the majority of their original glazing). The apertures of the side aisles are largely glazed with modern coloured glass, but due to their limited size and lower transmissivity along with the density of columns in St-Serevin, they are not likely to be important contributors of light in the nave. One factor that may slightly reduce the intended nave lighting, however, is the present concealment of the west rose (Window 221) behind an organ. Exterior obstructions do not appear to be an important factor, as many of the buildings have medieval origins and are limited in height (allowing the clerestory to possess a nearly full sky view). These features do, however, significantly limit aisle lighting, which is anachronistic and of little interest to us in any case.

The results between two analyses (one in the late spring and another during the winter) yielded highly precise daylight factors, and the averages of the two rounds are shown in Figure 4.30a. These measurements clearly indicate horizontal daylight factors range between 0.071% and 0.14%, which is as much as double or more the illumination expected for a thirteenth century full-colour interiors in both low and high-ceiling spaces (for example, the choir of Tours or Le Mans and the outer ambulatory of Bourges). Like in the Lady Chapel at Évreux, the

nave/choir measurements demonstrate a hemicycle signature, with illumination becoming markedly higher approaching the choir. This confirms the predominance of the clerestory windows in the nave lighting, and it is likely a product of the lower elevation of these windows with respect to the measurement plane compared to larger cathedrals. The hemicycle effect also produces the greatest interior illumination at the altar, probably a strategic goal of the interior light design of this establishment. Daylight factors in Figure 4.30b are calculated from the winter round of measurements, and comparison with the averages in Figure 4.30a indicates that the winter measurements probably slightly underestimate the actual daylight factor for most points except near the hemicycle. This should be kept in mind when observing the inner side-aisle measurements, which appear to be even brighter for the north inner aisle measurements than for the nave (perhaps due to the more unobstructed view of the south-facing clerestories), which are also elevated above typical levels seen for full-colour interiors in the inner aisles especially. The peripheral side-aisle daylight factors also confirm that the illumination of the nave is largely dominated by the clerestories. When compared to the larger, full-colour cathedrals in Section 4.2.2 above, St-Serevin presents a lighting improvement over predominately coloured programs from the thirteenth century.

However, St-Serevin's glazing is heavily coloured, with particular prominence given to rich blues, one of the post-grisaille revolutions darkest colours as discussed in Section 4.5. Many other churches on the scale of St-Serevin constructed during the Renaissance possessed much greater quantities of high translucency glass with lighter colouration, and thus as smaller structures they have the potential to possess much higher daylight factors than cathedrals with similar glazing. The churches of St-Panteléon and St-Nicolas, both in Troyes, are particularly good examples, as most windows in both interiors contain original Renaissance glazing. Overall, the glass in both churches is much less richly coloured than in St-Serevin. However, a potential complicating factor is provided by the fact that both churches also contain a large number of modern white quarries replacing the original renaissance glazing (likely of a similar design), particularly along the north side aisle and in some clerestory windows (see Grodecki et al., 1992; Minois, 2005). Darker, more richly coloured glazing from the nineteenth century is also present along the east end of St-Nicolas.

In general, the results obtained for both churches, presented in Figure 4.30, provide daylight factors that are much more elevated than in St-Serevin, ranging largely from 0.3% to

1%. Because they represent a mixture of Renaissance and modern white glass, contrary to St-Serevin they likely demonstrate the upper limit of likely daylight factors in a classic Late Gothic/Renaissance sacred structure. The south aisle of St-Pantaléon, which probably contains the most complete series of original windows (Figure 2.3), has daylight factors around 0.40-0.50%, still highly elevated compared to other interiors. In addition, vertical daylight factors facing the south chapel windows range between 0.10% and 0.17% (comparable to or slightly less than those in Évreux). Because St-Serevin is so strongly coloured and the Troyes churches are heavily white-dominated, most Late Gothic and Renaissance churches are likely to have interior illumination that fall between the two extremes, and in all cases notably brighter than the interior lighting aesthetic afforded by the older full-colour programs.

4.3.3: Troyes Cathedral Nave

Troyes Cathedral provides another important establishment that embraces the heavily coloured, high translucency tradition of Renaissance glazing. Its nave was largely constructed and glazed in the fifteenth and sixteenth centuries, and thus is represents a Renaissance construction project, unlike St-Serevin, executed on the scale of a cathedral. As such, it will help us confirm the lighting levels seen in other large-scale Late Gothic establishments. In addition to Renaissance glass, the nave also retains a scattered collection of glass from the fourteenth century, particularly in its aisle windows. In order to document the lighting in Troyes, daylight factors were calculated for one round of measurements, with exterior horizontal illuminances varying largely between 3500 and 10500 lux on an elevated bridge with minimal obstructions. Some unequal brightening to the west was present, but only in a few measurements. Several further considerations, however, must be taken into account when analyzing the daylight factors in terms of the contributions of the original windows. First, the interior can be subdivided into two sections, with its Late Gothic nave and largely High to Rayonnant Gothic choir and ambulatory. Each section possesses large quantities of glass from its particular era, best-preserved in the clerestory, although restorations in the choir and damage from a fire in the nave have taken their toll (see Grodecki et al., 1992). Otherwise, we consider the glazing for the nave clerestory and transepts to be relatively representative of the intended Late Gothic glazing.

Many of the windows of the nave side aisles and choir triforium suffered immensely during the French Revolution, as they were extensively destroyed to admit more light into establishment for its functions as a state temple. Thus, despite the overall good preservation of

the nave clerestory windows, today many of the side aisle chapels are filled with glass from the nineteenth and twentieth centuries which provide excess light contaminations. In particular, twentieth century lozenge glass installed in many of the sizable (8 m long, 4.8 m wide) apertures. The eastern architectural bays of the nave (see Figure 4.31a) and side aisles are thus perhaps the most representative of the original lighting levels. For example, Windows 47 and 49 retain the majority of their original glazing (however, Window 47 has modern coloured glass in its tympanum, and one of the six lancets in Window 49 is filled with white modern lozenges). On the south side aisle (Windows 32 and 34), nearly half of the lancets are provided with modern glass, and original fragments are heavily restored. In the western half of the nave, Windows 36 and 40 have two lancets (of six) filled with white lozenges, whereas Windows 38 and 53 are nearly entirely glazed in the same modern white glass (except for the heads of the lancets and the tympanum in the upper portions of the windows). Other nave chapel windows have a mixture of modern glass; for example, Window 53 affords a collection of grisailles and yellow stain fragments mixed with modern white lozanges, and Window 51 has original glass in the upper registers of the lancets while maintaining nineteenth century coloured glass to complete the ensemble in the lower part of the lancets and the tympanum. In addition, it should be noted that the exterior obstructions (adjacent ecclesiastical constructions, such as the large Chapelle des Catéchismes off the south side-aisle) appear to have a greater influence on the interior lighting on the south side of the cathedral than on the north side, although virtually all exterior obstructions (such as these and the Episcopal palace) have their origins in the medieval or Renaissance periods.

From the horizontal daylight factors in Figure 4.31a, it is clear that the modern contaminations have a significant impact on the lighting in the inner side aisles off the nave. In particular, almost entirely white Windows 38 and 53 demonstrate significant illumination peaks in their aligned inner nave aisle architectural bays. However, the data also suggests that the influence of the direct lighting from the side aisle peters out in the in the inner nave. Specifically, the greatest contamination lighting from modern windows in the side aisle is clearly located in the western nave. However, horizontal daylight factors in this region are slightly lower (0.170%-0.197%) than those in the eastern nave (0.215-0.216%), where there are white glass panes in the aligned side-aisle windows, presenting a classic nave signature in illumination (increasing illumination away from the west front). The higher values (0.188% and 0.197%) are in nave

bays aligned with predominately white Windows 38 and 53, whereas the lower value (0.170%) is associated with decreased north and south nave VDFs (not shown) associated with less white glass in the aligned side aisles.

Thus, if these three western nave architectural bays were to be treated equally, the contribution of direct lighting from the more modern lancets in the western nave appears to be associated with an addition of 0.02-0.04% to the daylight factors in corresponding sections of the inner nave horizontal daylight factor (only about 10-20% increase in the total value of the nave horizontal daylight factors). For the eastern nave, the east-facing vertical daylight factors are greater than in other sections of the nave. However, contamination lighting from the ambulatory windows is probably not important in these nave bays, as the closer crossing measurement shows a notable drop off in daylight factors for all directions. Given these results, we can generally expect the nave and side aisle measurements to have daylight factors ranging from 0.15% to 0.25% in the nave given minimal modern contamination lighting. This is well over double the daylight factors in thirteenth century coloured interiors, and for some points the illumination is just under an order of magnitude greater than thirteenth century daylight factors.

The transept daylight factors are also particularly high (0.28-0.31%). This might be partly attributed to internally reflected lighting from nearby modern ambulatory windows, as is also evidenced by Évreux's comparatively low daylight factors in this region. However, east-facing vertical daylight factors in the transepts are no greater than in any other direction. In fact, only the north- and south vertical and 45°-facing daylight factors (not shown) are slightly elevated (among the four points averaged together) compared to the east and west directions. Thus, transept lighting appears to be particularly elevated in a large part due to the direct lighting and internal reflections associated with the transept windows themselves. Given distances from the contamination light sources, even with completely original windows filling all apertures of the interior we would not expect the transept daylight factors to fall much below 0.15% (half of the values received). Thus, the measurements from Troyes Cathedral reveal that Renaissance glazing, even when as richly coloured as at Troyes, does appear to provide much more light than full-colour windows in thirteenth century interior under cloudy conditions.

Another way of illustrating the differences between thirteenth century and Renaissance lighting at Troyes is by analyzing the illumination of forms high up in the cathedral, which like in other examples are further removed from the aisle-level contaminations from modern

grisailles compared to the illuminance measurements. In addition, both the nave and choir have nearly equivalent window length to height dimensions (choir clerestory: 6 m by 10 m; choir triforium: 2.50 m by 6 m; nave clerestory: 6 m by 10 m; nave triforium: 3.5 m by 6 m); thus we would expect glazing transmission to be the primary control on the luminance values received on interior surfaces that have the same reflectances between the two regions. Indeed, a reflectance comparison indicated that the average reflectance of the stonework for three samples was 48% (a typical value), and reflectance differences were negligible between the sections of the interior (one nave sample had reflectance of 46%, one in the choir 54%, and another in the choir 45%). Four photo series were taken, one highlighting the north side clerestory of the nave and choir together and one of the south sides of the nave and choir (see Figure 4.32). The choir photos were taken first under an overcast sky with a very slight brightening to the west but nearly equal illuminances in the other directions. To ensure a similar sky luminance profile, a photo series was taken of the choir first and immediately thereafter of the nave (most photos were taken for the two series within six minutes of each other).

In both cases, the choir measurements were taken first, and the declining sun at the time suggests that, assuming the cloud cover consistency remained the same, the background exterior luminance distribution for the choir measurements (under a thirteenth century full-colour aesthetic) should be greater than for the photo series taken in the nave if both sides of the cathedral possessed glass with the same glazing transmission. Furthermore, the greater contamination lighting in the choir, from both the side aisles (as seen in Figure 4.32a and 4.32c) and the heavily restored triforium glazing would also favour greater lighting of forms in the choir over the nave. However, Figure 4.32 reveals that, even with the preferential disposition of the choir to have greater lighting, the nave possesses notably higher luminances over almost all surfaces compared to that of the choir. Much of the triforium tracery and piers of the nave in particular are more than double the luminances seen for similar points in the choir.

These results, indicating nearly a doubling of luminances on forms in Renaissance interiors (compared to full-colour, Rayonnant programs), are consistent with those obtained for other grisaille-dominated and Late Gothic interiors in Section 4.2.3. Therefore, it appears that the more richly coloured Renaissance glazing traditions common in France in the fifteenth and sixteenth centuries continued to provide greater illumination to forms on a level comparable to that seen during the grisaille revolution. This, in turn, isolates the grisaille revolution during the

turn of the fourteenth century as a single, permanent shift in interior lighting aesthetic, not to be changed during other periods despite the return to more glazing coloration during the fifteenth century.

4.3.4 The Abbey Church of St-Ouen

Much like Évreux and other Late Gothic projects, St-Ouen, with its vast window space, was largely glazed over the course of the fourteenth and fifteenth centuries. Today, the choir preserves a wealth of stained glass fragments that date to the first half of the fourteenth century and are treated with a similar band window formula as observed in Évreux. However, many of the choir windows, and especially those of the ambulatory, also contain large quantities of modern grisaille glass. Unfortunately, the church's glazing has been altered over the centuries by a series of misfortunes, including those inflicted by restorers in the nineteenth century, and thus many of the grisailled tympanums in the nave have now been replaced with modern ornamental white glass (Callias Bay et al., 2001). While this glazing, stylized after the original, might possess a similar clarity as the ancient glass during the time of its first installation, for the purposes of this study it is viewed as a contamination. In general, the windows in the nave clerestory have greater quantities of original glass (most dating from the end of the fifteenth century and beginning of the sixteenth). However, while all windows of the nave and side aisles also possess some quantity of stained glass from the Renaissance, they also all retain a significant proportion of modern glazing (Lafond et al., 1970). Thus, it is useful to analyze the nave and side aisles of St-Ouen as an upper limit to the possible illumination in a Renaissance nave.

Within this context, few other contaminations are provided that would significantly influence the values obtained by the instruments, beyond some scaffolding near the eastern parts of the south aisle and over the south transept rose. The measurements in St-Ouen were taken with Instrument 2, and only values falling under 20 lux (one measurement in the south transept) were upward-adjusted according to the formula in Appendix II). Thus, the interior values might be slightly lower than the Instrument 1-equivalent in some cases, although the slightly more obstructed location chosen for exterior measurements (in the centre of the field east of the church, ringed by trees along its periphery) likely restricts the values of exterior illuminance (probably not by more than 10% of the unobstructed value, given data from Tours and Angers).

Thus, for our purposes, the two sources of error (both underestimations) likely cancel each other out during the calculation of daylight factors (determined for only one round of measurements).

First, it is useful to analyze the daylighting in the ambulatory of St-Ouen. Only estimated daylight factors (under thick stratus/fog, with exterior horizontal illuminances approximated from a background radiation trend obtained during operations at Tours) are available for sections of the ambulatory. The modern glazing actually appears to provide substantially more illumination to the interior, with estimated daylight factors between 0.52% and 0.92%, higher than values at Évreux (0.15-0.4%). Similarly, St-Ouen's apse chapel daylight factors of 1.4% and 3.11% contrast significantly with daylight factors closer to 0.20%-0.40% under the coloured Renaissance glass of the Lady Chapel in Évreux. Thus, ignoring the differences in the geometries of the two constructions, the results from St-Ouen's mixture of ancient and modern glazing appear to be approximately double or less what might otherwise be expected with more original glass. Thus, we would anticipate that the persistent inclusion of modern glass in the nave windows would also increase the ambient illumination compared to what might have been the case for the original program.

The results for horizontal daylight factors in St-Ouen are shown in Figure 4.31b, and they appear to provide similar readings as the interior of Troyes Cathedral. The side aisle architectural bays of Troyes containing strong contamination lighting, for example, have values that closely mirror those for St-Ouen. Both the horizontal daylight factors in the nave and side aisles and the vertical daylight factors in the nave reveal that the greatest lighting appears to come from the south aisle windows, despite similar exterior obstructions for both sides of the nave. Even provided with a dark, consistent overcast, some brightening toward the sun might have played a role in this inequity. The nave lighting in St-Ouen is greater than at Troyes but not dramatically so, perhaps partly as a result of the higher elevation of the aisle-level windows and 9 m closer proximity to the central nave. Thus, central nave daylight factors ranging generally from 0.25-0.4% appear to provide an upper limit for the transmissive ability of Renaissance glazing, with most locations in interiors maintaining most of its Renaissance glass likely falling below these levels. Furthermore, a series of approximate daylight factors (not shown) were also evaluated for the nave of Amiens, which is today glazed nearly entirely with white modern lozenges. It retains somewhat higher daylight factors, largely between 0.21% and 0.32% in the nave, 0.51% and 0.74% in the north aisle, and 0.51% and 0.64% in the south aisle. Thus, the

ambient illumination of Troyes's nave (0.15-0.21%) appears to be an adequate representation of the middle state of Renaissance illumination. St-Serevin, on the other hand, provides an example of slightly lower daylight factors between 0.07% and 0.15%. The likely daylight factors for other original interiors to the Renaissance probably falls somewhere between the two (0.15%), which is three to eight times greater than typical values under full-colour interiors. The daylighting differences between the full-colour aesthetic and later regimes is enough to be noted qualitatively by human observers (Lillich, 1994).

Therefore, the results from St-Ouen confirm that the upper limit of Renaissance glazing on illumination in the nave is just under one order of magnitude greater than the full-colour illumination, with most Late Gothic glass providing somewhat less than a one order of magnitude improvement in ambient illumination during cloudy conditions. In addition, from results from Troyes, Renaissance glazing appears to provide similar ambient illumination to grisaille-dominated interiors such as Évreux, or perhaps slightly less when richer colouration is used (such as in the Évreux Lady Chapel). In addition, the contrast of architectural illumination under overcast conditions between the Renaissance and the thirteenth century does not appear to be markedly different than that seen between the thirteenth century and grisaille revolution programs (Cologne, for example). Therefore, our results confirm that Renaissance glass continues the tradition of higher translucency windows and greater interior illumination for cloudy conditions started during the grisaille revolution.

4.4 Mediterranean Interiors

As mentioned in Chapter 3, French cathedrals were selected as the primary focus for this study and were highlighted in the above three sections. English and Mediterranean sacred interiors were only treated qualitatively in the introduction. Based on full-colour examples in northern France, it is possible to make general assumptions about the function of heavily coloured or mixed glazing in the Mediterranean. However, many Mediterranean churches and cathedrals have different orientations and architectural characteristics compared to their northern counterparts. For example, most Spanish cathedrals retain a large choir in the centre of what is traditionally the nave in French cathedrals, while the traditional 'choir' location (in French structures) is often abbreviated and is instead home to an often elaborately-decorated altar space. In addition, Mediterranean church windows, often smaller than northern apertures, are also frequently more prominent at the clerestory level instead of the aisle level. Therefore, we

obtained several series of measurements in a few Spanish cathedrals, and the results from these data collection surveys are briefly summarized here. Outside of León Cathedral, virtually all Spanish stained glass dates from the Renaissance era. For this reason, we also wished to determine if Renaissance glazing in Spanish churches provides as much interior lighting as French Renaissance programs.

4.4.1 Toledo, Sevilla, and Segovia

Toledo Cathedral perhaps affords the best preserved stained glass interior from Spain, with much of the glazing dating from the Renaissance. Additionally, its windows were relatively well-maintained at the time of measurements, providing an excellent interior to analyze. However, the cathedral was extraordinarily dark on the cloudy day chosen for interior measurements; even with the ambient artificial lighting our meters consistently provided a 0 lux reading on the interior with exterior horizontal illuminances ranging between 8000 – 3000 lux (typical winter overcast readings). We obtained one reading of 1 lux at the crossing using Instrument 3, which likely represents 2 lux on Instrument 4. This would yield an Instrument 4-equivalent daylight factor of 0.029%. Given that the maximum Instrument 4 value for an Instrument 3 reading of 0 lux is 2 lux, we calculated 2 lux divided by the exterior horizontal illuminances at the times of measurement to determine maximum possible daylight factors in the transepts (0.032 to 0.043%) and the ambulatory (0.044% to 0.060%) given the background exterior horizontal illuminance. All other points were taken when the exterior horizontal illuminances were too low for interior readings. Even when provided with significant brightening toward the sun on a second visit to Toledo, the daylight factor estimates in the inner side aisle of the nave ranged largely between 0.016% and 0.055%. More precise measurements could not be obtained during our experiment due to volatile weather conditions (and exterior horizontal illuminances that were too low for interior readings). Thus, for more accurate, absolute daylight factors for particular locations, another round of measurements would need to be taken on a bright, cloudy day. However, our preliminary results suggest that the transepts, crossing, ambulatory, and nave are likely much darker than Renaissance interiors in French churches, which (with daylight factors of 0.1-0.2%) would likely register values well above 0 lux on Instrument 3 (approximately equivalent to 1 lux on Instrument 1 or 4) for most of the measurement period (where exterior horizontal illuminances were nearly always greater than 2000 lux). However, no value greater than 0 lux was obtained after exterior horizontal

illuminances fell below 6230 lux. While perhaps in part due to a lower window transmissivities, the lack of low elevation aisle-level windows in the cathedral undoubtedly contributes to the low illumination near the ground level.

Therefore, Toledo Cathedral, despite its use of Renaissance glazing, possesses daylight factors more typical of full-colour French interiors, rendering it virtually as dark as Chartres. This is true in spite of the cathedral's relatively large clerestories (for a Mediterranean cathedral) and its profuse interior sculpted decoration, such as on the choir screen, which would require as much daylight illumination as feasibly possible. Measurements during periods where the solar disk was partially visible (i.e, a brief period of sustained sunshine) with a surrounding stratus overcast, however, indicates that interior horizontal illuminances may range between 5-18 lux (Instrument 4 values) in the nave. Thus, under full sun, even higher interior illuminances can be expected, and these would serve to illuminate the forms and decoration of the cathedral. Therefore, it appears that the Renaissance Spanish glass may provide lower or equivalent illumination to full-colour interiors during overcast conditions, but for periods of sunshine the interior may be as bright or brighter than a French interior with predominately coloured glazing. This greater illumination, in turn, provides better lighting of the intricate and rich artistic works of the interior. Therefore, it seems plausible that Toledo Cathedral and its windows were designed with an assumed clear sky exterior illumination pattern, and this seems reasonable given the modern cloud climatology of the Mediterranean basin in Meerkötter et al. (2004).

A very superficial analysis of the interior lighting of Sevilla Cathedral was also conducted under a winter overcast sky with an exterior horizontal illuminance of approximately 22100 lux during a period of slowly-varying background illumination and consistent mixed altostratus and altocumulus overcast. Sizable aisle-level windows are present in the interior of Sevilla Cathedral, but they are deeply recessed in chapels off the five-aisle nave. Even without the subtraction of the (likely substantial) artificial lighting component, the interior lighting ranged between 5 and 14 lux (Instrument 4) in well-preserved areas in the western nave in view of Renaissance windows, yielding (assuming all light to be daylight) estimated daylight factors mainly between 0.02% and 0.05%. Even in the crossing, where strong artificial floodlighting was present at the time of measurements, the values of 20 lux (again if assumed to be entirely daylight) produce likely daylight factors just below 0.1%, less than what would be expected in most northern French Renaissance interiors without any artificial lighting. Therefore, clearly

Sevilla Cathedral, which diverges strongly from the French models more commonly adopted in northern Spain, also possesses very dark interior lighting typical of French thirteenth century full-colour interiors and less characteristic of French Renaissance lighting. Thus we conclude that Sevilla may also be designed for maximum illumination under clear sky conditions.

Daylight factors obtained in Segovia Cathedral are perhaps the closest to those expected from a Renaissance interior in the north. The glazing of the nave was not in particularly good-repair at the time of measurements, and several apertures possessed modern restoration glass along with transparent white glass (which provided an important source for contamination lighting). Also, much of the glazing in the windows of the crossing and ambulatory regions are modern, providing for higher daylight factors in a few parts of the eastern nave. In addition, the nighttime artificial subtraction had to be completed slightly before sunset (1630 GMT, 20 December, 2008), which suggests that the daylight factors calculated may be slight underestimations of the actual value in a few cases. The average daylight factor across all points in the nave and side aisle is 0.05%. A few daylight factors which are closer to areas of modern glazing, such as the eastern end of the side aisles, have daylight factors closer to 0.06-0.08% , whereas those in some of the darker areas of the side aisles are particularly low, falling below 0.04%. Therefore, in some parts of Segovia Cathedral, the actual daylight factors are likely above those expected in full-colour interiors but generally less than those expected for most Renaissance-era churches and cathedrals in northern Europe (0.8%-0.2%).

4.4.2 León

While cloudy weather illumination in many Spanish Renaissance interiors appears to be approximately equal to or less than that for French thirteenth century coloured programs, sunny measurements appear to provide markedly elevated illuminances across much of the interior. For example, León Cathedral provides a particularly important example of a Spanish full-colour interior with traditional pot metal glass surviving from the thirteenth century. It was designed by a northern architect but still retains several local adaptations, including, one might argue, the richly-coloured glass used to fill the apertures. Several of the windows are heavily restored, and the prominent aisle-level apertures of the nave are now glazed with modern, somewhat corroded ornamental coloured glazing. There are some restrictions on lighting in the interior; in particular, in the central nave hemicycle, Window 200 (the central hemicycle clerestory lancet) and Window 201 (the clerestory lancet to the left of Window 201) were covered (with exterior and

interior scaffolding), as were the windows in the south nave triforium in the eastern three-fifths of the nave. In addition, wooden platforms were positioned between Windows 200 and 206 (the hemicycle lancets) as well as over the first architectural bay of the nave, providing shading in theses regions of the nave and choir. However, overall the values obtained are expected to be representative of full-colour lighting, and it may provide an indication of the interior daylighting in early thirteenth century establishments in northern France, such as Chartres, before the present corrosion of the clerestory windows.

The results (Figure 4.33) indicate that the sacristy and oratory to the south radiating chapels prevents the same kind of ambulatory illumination as seen in Bourges, where intense solar radiation in the south ambulatory during the winter provides excess illumination across much of the interior. A more Bourges-like profile is likely, however, in the hours after sunrise between the equinoxes. The effect does, however, ensure maximum illumination in the ambulatory bay adjacent to the Lady Chapel, with horizontal illuminances approaching 7-8 lux and higher south-facing directional illumination. Adjacent bays in the north ambulatory have even greater illumination, with high southerly and westerly illuminance values. This is provided by solar lighting from the clerestory on the north side of the altar/choir (thus, the values obtained appear to provide an indication of the magnitude of the clerestory lighting contribution to the choir). The crossing is one of the brightest areas in the cathedral, with the sun's most direct illumination falling on the south rose window. This appears to produce an illumination maximum just west of the crossing. For times of the year with higher solar angles, this maximum illumination would likely fall on the crossing. In general, throughout the transept/crossing space, illuminance readings are as high as 11-20 lux, approaching 40 lux in the south-facing directional measurements. The greater lighting in the crossing and transepts could, in turn, provide enhanced luminances to the interior of the choir and altar areas. The high values seen in León contrast markedly with the only 6-9 lux values, even for directional measurements, seen near the crossing for clear sky measurements in Chartres at 1005 GMT on 2 June, 2007 (with the very poor preservation of the south rose window). Thus, when provided with clearer clerestory glazing, Chartres probably saw much greater interior illuminances at the ground level under sunny conditions than are observed today. The nave measurements in León Cathedral also appear to be dominated by direct sunlight through the aisle level windows, which provides brighter illumination (10-30 lux) for most locations west of the nave-choir structure.

4.4.3 Santa Maria del Mar

In addition, a series of sunny-weather measurements were also taken in the much broader church of Santa Maria del Mar in Barcelona, which possesses a central aisle nave more typical of French interiors (however, aisle-level windows, like in many Mediterranean structures, are minimal). The church also contains a mixture of coloured modern and Renaissance glass, with much of the West Rose window retaining its original glazing (Ainaud de Lasarte, 1985). With the west front windows receiving illumination from the solar disk, estimated nave horizontal illuminance values (with subtraction of artificial illumination) appeared to be centered around 30 lux (with some locations falling closer to 11 lux and others, under the direct rays themselves, as high as 60 lux). Earlier in the day when the sun was aligned closer to the south facade, inner nave measurements only approached 11 lux. Thus, Santa Maria del Mar, demonstrating a range of values similar to León Cathedral, experiences concentrated illumination under clear sky conditions. The highest values were obtained with the west rose lit directly by solar radiation, which perhaps strategically often occurs around midday given the north-northeast-pointing axial orientation of the church choir.

In summary, the largely Renaissance-glazed cathedral interiors in Spain possess, with relative consistency, daylight factors typical of full-colour interiors in France. Therefore, it is clear that the Mediterranean interiors, with their generally smaller windows, fewer aisle apertures (clerestory-dominant interior lighting), smaller window-space to-wall-space ratios, and often more prodigious use of richly coloured glass, are significantly darker than their French Renaissance counterparts. The very fact that illumination in these Mediterranean interiors, widely acknowledged for their design for sunlighting illumination (M. Lillich, Personal Communication, 2008; Charles Sherrill, 1927; Wachs, 1964), perform similarly to full-colour interiors in northern France under cloudy conditions further suggests that French coloured interiors were designed assuming a prevailing solar illumination. In other words, the Mediterranean daylight factors (with their dark interiors under cloudy conditions and much greater illumination under sunny skies) represent a signature associated with optimal interior solar daylighting, and the consistency between the daylight factors in full-colour interiors in French churches and later Spanish cathedrals indicates that early thirteenth century French interiors may have been designed for sunny skies.

This idea is reflected in the words of the Chancellor of Chartres around 1200, who wrote "the glazed windows in the church..transmit the clarity of the sun, representing the holy scriptures. They fight off the bad in us while enlightening us all (*tout en nous illuminant*)" (Grodecki, 1983). The emphasis on solar lighting thus appears to be important, at least in this particular textual source, and it may be possible to link the lighting strategies of Mediterranean churches (with climatologically-assumed solar lighting) and coloured French interiors given their similar performance under cloudy and sunny conditions. Therefore, our survey of Spanish, largely Renaissance constructions appears to confirm a persistency of interior lighting strategy in the Mediterranean basin. This architectural lighting performance is on par with the illumination provided by thirteenth century French coloured interiors but not later, grisaille, flash, or enamel-glazed interiors from the fourteenth century onward. In turn, given the persistency of solar illumination design in the Mediterranean, this puts the later French programs within the context of a lighting design meant more to accommodate persistent overcast conditions. Thus, the Mediterranean story places further significance on the possibility that cloud cover increases (or the perception of persistent cloud cover) in northern Europe may have played a role in the conversion to whiter glass.

4.5 Differential Relative Transmissivities

Another way of illustrating the differences in lighting between Late Gothic, grisaille revolution, mixed/full-colour, and modern programs is by analyzing the luminances of the window panes themselves rather than the interior side walls that they illuminate. This technique allows us to obtain a measure of mean transmissivities of different types of glass relative to each other, which is possible when fragments of one type of glazing are mixed with that of another in the same HDR photo series (for example, Renaissance glazing combined with early thirteenth century glass). We can make the general assumption that adjacent panes of glass receive similar exterior luminances and also similar quantities of internally reflected illumination. Thus, the differences in the luminance values between two panes of nearby glass are largely a function of their combined transmissivities and reflectances relative to each other. For glass, transmittance is generally more important than reflectance, assuming that interior illumination does not overpower the transmittance (which produces the observable effect of backlighting). Of course, the unevenness of the panes would affect the luminances as perceived in a particular direction, but this is a concern for virtually all glass panels.

Thus, we took HDR images of windows, usually receiving diffuse radiation and experiencing significant backlighting, to analyze the relative transmissivity of glass. This can be important for determining the differential transmissivity from well-preserved panes dating from the same era (for example, how much more transmissive white, pink, or yellow thirteenth century glass is compared to deeper reds and blues), allowing us to calculate the light-admitting capacity of a window based on its colour composition. In addition, with mixed glass from different eras, it is possible to make a direct translucency comparison between similarly coloured glass produced during different epochs (for example, white thirteenth century glass and white Renaissance glass) to determine the role of technological advances in the increased illuminances of interiors. The HDR photo series thus enables us to make a high resolution luminance comparison, aiding in the understanding of changes in window transmissivity for different periods in glazing style and design.

Our first objective is to identify whether or not technological considerations were a primary limitation on the transmissivity of a window style (and thus interior illuminance), or if the chosen palette was the primary controlling factor. First, we performed an analysis of Romanesque glazing, and the example presented here is taken from Notre-Dame-de-la-Belle-Verrière (Window 30, Chartres Cathedral); its light blues and red appears to have a palette similar to that of early stained glass in France. In the Romanesque tradition, red was frequently used, but often as a background colour to provide contrast rather than a dominant element of the window (Grodecki, 1983). The predominate colours of the windows, such as seen in the twelfth century Virgin at Vendôme, were often more translucent yellows, whites, and light blues, the latter colour being very similar to that seen in the surviving Romanesque panels of Notre-Dame-de-la-Belle-Verrière. In this case the light blues of the Virgin's robes are particularly well-preserved, and the Romanesque glass is surrounded by rich, saturated red and blue-dominated Gothic panels. A luminance estimate profile provided by an HDR image of a restricted section of the window is seen in Figure 4.34 (and as such we can probably assume that most of the panels in the figure receive approximately the same amount of exterior illumination). Comparing the luminances (Figure 4.35a) of different colours (Figure 4.35b), the darker Gothic blues are associated with luminances of only 0.1-0.2 cd/m^2, whereas the light Romanesque blues are much more transmissive, mostly above 0.5 cd/m^2.

Therefore, the light blues common during the Romanesque period are several times more transmissive than the gothic blues, and only the scattered white and pink Gothic glass rivals the light blue in translucency. From this example, the colour palette appears to be the dominant factor in glazing transmission, rather than the Romanesque technology to produce clearer, more translucent stained glass. During the gothic era, the richer, Chartrain-style glass, dominated by dark blue and red (the two least transmissive colours available in the rich palette of the mosaic glass tradition) was less transmissive than Romanesque glass, which balanced a mixture of much brighter colours (such as light blue) with some richer colors (such as red). The red patches of glazing in both the Romanesque and Gothic sections of the window in Figure 4.34 appear to have comparable transmissivities. It also turns out that red proves to be consistently the lowest translucency glazing throughout stained glass history. Because a pure red panel would be opaque, red glass has always been flashed in a manner similar to what was more commonly used for Renaissance glazing (Raguin, 2003).

Analyzing the luminance profile of thirteenth century pot-metal glass (Figure 4.30) also provides a useful representation of how the colour palette influenced the transmission of light. The HDR luminance capture approach does not respond equally to all colours, as demonstrated for reflectance values of different Munsell hues and chromas (especially blues and greens) in Moeck and Anaokar (2006). However, because a translucent medium (glass) is being analyzed we will assume that transmissivity of a certain colour rather than colour itself provides the dominant signal in the luminance values obtained. This approach appears to be validated by the results above in Figure 34. As red glass appears to have a relatively stable, low transmissivity across the ages, it was used as a standard for comparison. With a sampling of adjacent panels from two windows in Chartres, one the north rose and lancets (Window 121) and the other at the aisle level (Window 41), stable averages of relative transmissivity were obtained. The results essentially confirm findings by Sowers (1966), with blue averaging two (or as much as three for light clerestory blues) times more transmissive than red (and seven to eight times less tranmissive than white), yellow/orange between six and eight times more tranmissive than red, and white between 10 and 12 times more transmissive than red. Windows that are entirely white clearly have a greater translucency than those that are fully red; however, every window is composed of varying quantities of different glass colours and surface geometries.

The end result is an additive illumination that is a reflection of the combined effect of different colours. In the case of the rose window lancets, their average for red across the south rose lancets, at 1.93 cd/m^2 for 64 reference samples, is just under two times the average luminances for the five north rose lancets together (3.69 cd/m^2). Thus, the combined effect of the colours seems to provide a total transmissivity that is closer to that of what we would expect from an entirely blue window. In other words, the slight brightening effect of blue and much greater degree of brightening of white and yellow, mixed with the greens, darker reds and some blackened corroded glass, produces a combined transmission equivalent to that of an entirely blue window. Therefore, the thirteenth century palette provide values that are skewed toward the low end of the transmission spectrum, closer to the reds and blues than they are to the brighter colours. Thus, the full-colour tradition in early thirteenth century France, from this limited analysis of the glass of Chartres, appears to be responsible for the low interior illumination in interiors provided with red and blue-dominated full-colour windows.

These tendencies, however, do not necessarily apply to grisaille windows, which use the much more translucent (by as much as three times greater than the average lancet luminance in the example above), whiter glass. The effects of white glass in more grisaille-like windows can also be evaluated when mixed with coloured windows, perhaps most aptly for the well-maintained glazing of Cologne Cathedral. Figure 4.36 provides a perspective of the south clerestory, centred on Window SVI (numbered according to Herbert, 1974), which retains approximately 90% of its original ornamental glass. The broad swath of the coloured band on this window corresponds to luminances nearly exactly half those of the grisailles. Smaller scale analyses (to eliminate the effect of sky luminance distribution) exhibit the same tendencies, with the grisaille window panes just slightly more than double those seen for other windows. Like at Chartres, blue demonstrates a slight improvement over red (largely between 20-30 cd/m^2, whereas red glass was between 5 cd/m^2 and 20 cd/m^2), orange between 40 and 90 cd/m^2, and yellow between 80 and 200 cd/m^2. The white grisaille glass above varies largely between 125 and 300 cd/m^2, and large pink panes within the composition had similar or slightly smaller values as white. With the combined effect of the coloured glass at 40 cd/m^2, the brighter, more varied colours of the German glass provide an average luminance that is greater than the blue panes averaging below 30 cd/m^2 Thus, the greater diversity in colour appears to give these windows a higher total transmittance than the windows of Chartres, with its more prevalent rich

blues and reds. This is also true despite the fact that Cologne's colour palette adheres to the relatively saturated Rhenish tradition of red and blue backgrounds during the early fourteenth century (as noted by Grodecki and Brisac, 1985). Therefore, the glazing transmission data appears to validate earlier discussion that the brighter colour palette of germanic colour glass has greater illumination capability. The same results were obtained in St-Kunibert's, Cologne (not shown), where the central apse window demonstrated approximately four times greater luminance than the average of its red panels. A general improvement in the clarity of the German coloured glass is also perceivable, a product of the good preservation of the glazing and the inclination and position of the camera (greater inclinations associated with a view toward a brighter portion of the sky). However, for the values above, the relative transmissivities between individual colours are quite similar for the Cologne glass as seen in Chartres.

For a comparison of thirteenth century coloured glass to later Renaissance glazing, the cathedral of Rouen possesses two side-aisle windows (51 and 53 as labeled in Callias Bay et al., 2001) with a unique and particularly insightful combination of early thirteenth century, Renaissance, and modern glass. The HDR false-colour profile of Window 53, the Renaissance glazing of which has been less redone in the modern era, is provided in Figure 4.37 First of all, something that becomes readily apparent is that the red Renaissance glazing in the image does not appear to be any more transmissive than the thirteenth century glass above it. Therefore, the use of red appears to limit the amount of incoming radiation. However, the whiter panes used frequently in garments and flesh allow well over one order of magnitude greater illumination through the window. Richer blues, as seen for Window 51 (not shown), provides comparable to slightly greater luminance values compared to blues in thirteenth century windows, with the light blues in Window 53 possessing a greater transmissivity. Two other common Renaissance colours, such as yellows and light greens, like white also provide an enhanced translucency. The combined result for Renaissance glazing (with an average luminance of approximately 130 cd/m^2) is essentially nearly one order of magnitude greater than the average over the adjacent thirteenth century glass (between 11-13 cd/m^2).

Similar results were obtained from Troyes Cathedral (Section 4.3.3), where a sample of 50 red panels in Window 232 (see Figure 4.32 in Section 4.2.3) gave an average of 2.4 cd/m^2, whereas the total luminance of the window averages to 14.3 cd/m^2 (six times greater, more than twice that of Gothic blue at an assumed maximum of three times the transmissivity of red).

Thus, Renaissance glass clearly appears to provide markedly greater lighting than the thirteenth century glass, largely on account of its prodigious use of high translucency whites, yellows, light blues, and greens. The more strongly coloured (dominated by blue and red glass) Window 231, on the other hand, provides an average red luminance of 3.5 cd/m^2 and a total window luminance average of 10.9 cd/m^2. Thus, depending on the colour structure, richly coloured French renaissance glazing may provide three to six times more interior illumination than red Renaissance glass. However, it is also clear that, with a total average luminance more than three times greater than the average red pane, the translucency is still significantly greater than for Gothic stained glass. The end result of this greater translucency is the higher form illumination, as discussed in Section 4.3.3.

In summary, our findings have determined the relative glazing transmissions in various interiors using luminance data from HDR photo series, and a few of these results are presented here. The data indicates that red always has the lowest translucency (and likely stable absolute transmissivity across the ages), whereas white is naturally the brightest glass pane. Red, however, likely only increases slightly in its transmission capability, as it has always needed to be flashed in order to prevent opacity. As suggested by Grodecki, the palette of Romanesque glass appears to have favoured a greater glazing transmission, especially compared to early thirteenth century glass dominated by deep reds and blues. The Romanesque light blue, yellow, and Gothic white glass could clearly be several times brighter than the darker blues and reds used more frequently in the early thirteenth century. While Romanesque colours may not have provided an order of magnitude increase in transmission when compared to thirteenth century glass as Renaissance glazing clearly did, it probably lies somewhere between the two extremes (a large sample set of relative transmissivities between colours, with red used as a relative constant, would better establish the exact degree). Therefore, Gothic artisans had the ability to create significantly higher translucency iconographical windows than were actually produced in the thirteenth century. This suggests that the rich, saturated colours of the early and High gothic periods and their associated low transmission of illumination were very much a choice rather than a technological constraint. Renaissance colours, produced largely using flashed glass and enamels, possess similar glazing transmissions as earlier glass for reds and dark blues but retained large quantities of highly translucent white, light blue, yellow, and light green colours. The combined effect for colours in Renaissance windows analyzed in this study appears to be as

much as an order of magnitude increase in transmission, and this is similarly confirmed by daylight factors which are also as much as an order of magnitude greater in Late Gothic interiors.

Chapter 4 Figures

Figure 4.1: The state of the clerestory windows of Chartres (Windows 126 and 128 in Grodecki et al., 1981). The photograph was taken on 2 June, 2007 at 1315 GMT.

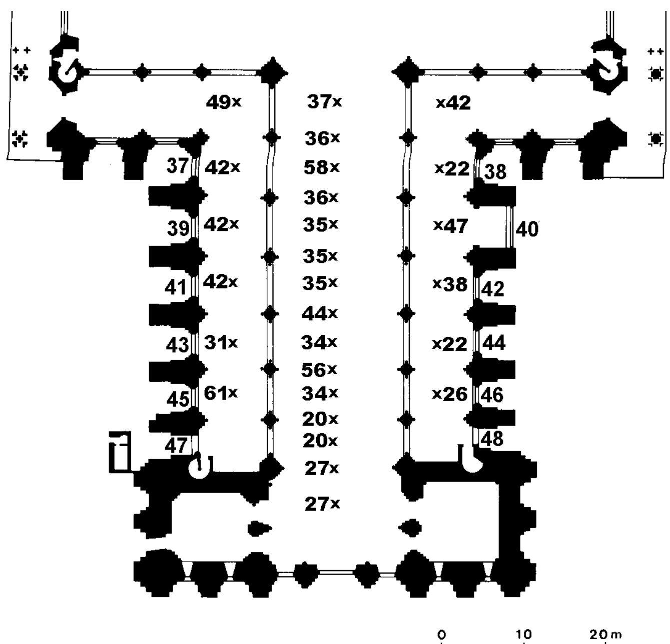


Figure 4.2 Horizontal daylight factors (multiplied by one thousand) averaged from two separate experiments in the nave and side aisles of Chartres Cathedral. Window numbers are indicated along the outside of the cathedral plan.

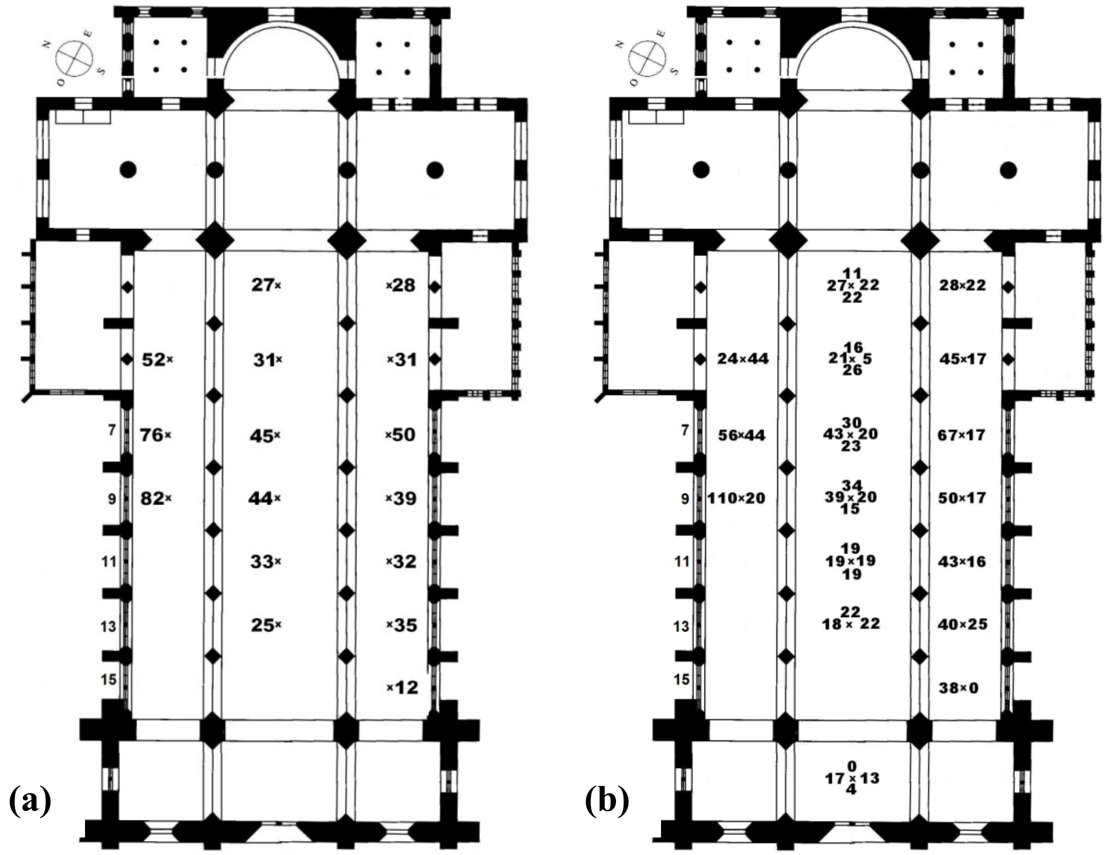


Figure 4.3: Daylight factors (multiplied by one thousand) in the nave and side aisles of Strasbourg Cathedral based on one round of measurements. (a) has horizontal daylight factors, and (b) has vertical daylight factor, with each numerical value facing its respective direction.

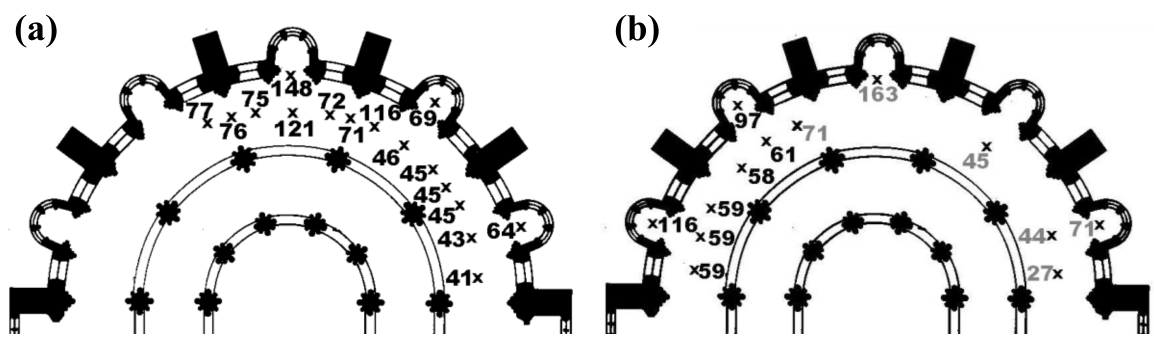


Figure 4.4: Approximate horizontal daylight factors (multiplied by one thousand) calculated for the ambulatory of Bourges Cathedral. In (a), daylight factors are determined for a CIE standard overcast sky (based on one round of measurements). In (b), daylight factors are averaged between a CIE standard overcast sky and a CIE sky standard 4, with the averages between high precision measurements shaded in grey. At locations 1 and 3 (as indicated in Figure 4.5 below) the average is taken between a standard overcast sky and a patchy overcast sky.

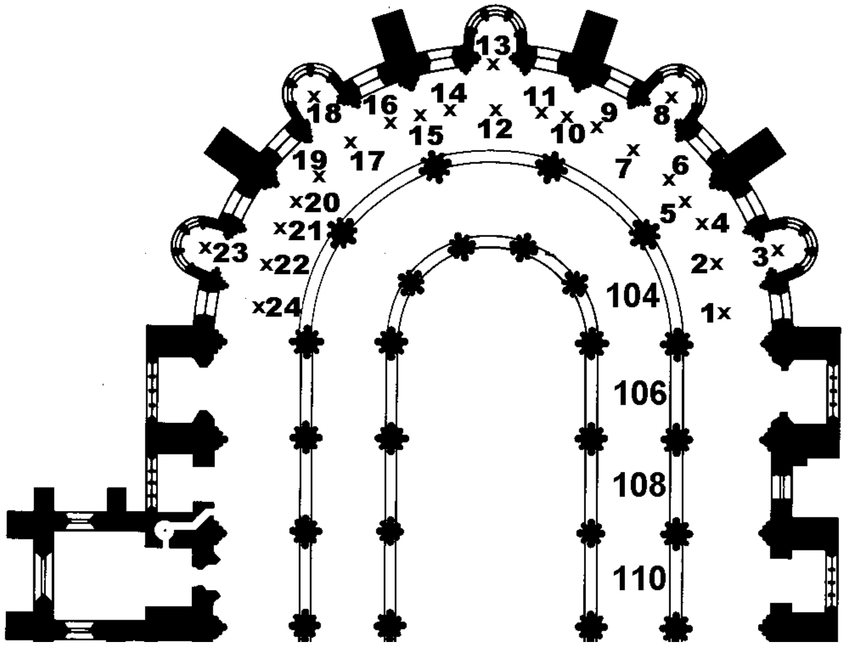


Figure 4.5: Location numbers in the ambulatory of Bourges Cathedral for Tables 4.1 and 4.2, with modern triforium windows labeled by their corresponding number in the south inner ambulatory.

Figure 4.6: A view toward the outer south ambulatory in Bourges, illustrating the deep penetration of light through the aisle windows in the winter. Image taken on 21 January, 2008 at 1125 GMT.

Figure 4.7: A view of the outer south ambulatory of Le Mans Cathedral at 900 GMT on 30 June, 2008, at a time when direct sunlight was being received by the cathedral's north clerestory windows.

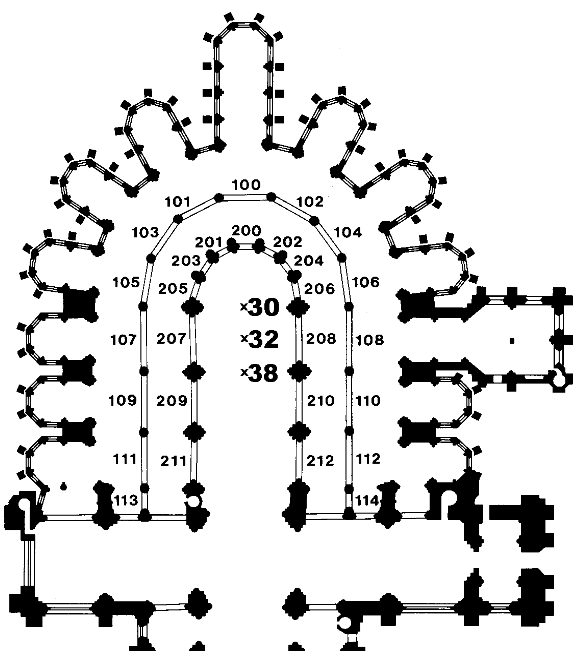


Figure 4.8: Daylight factors (multiplied by one thousand) in Le Mans Cathedral's Choir

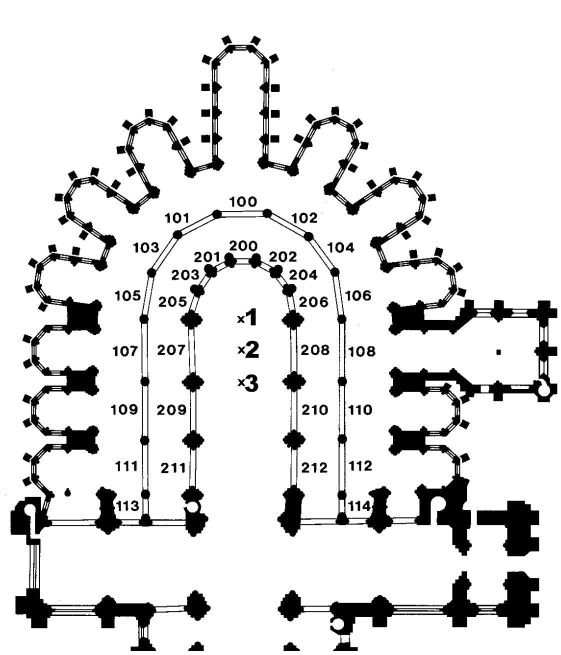


Figure 4.9: Location numbers for the choir of Le Mans Cathedral (used in Table 4.3)

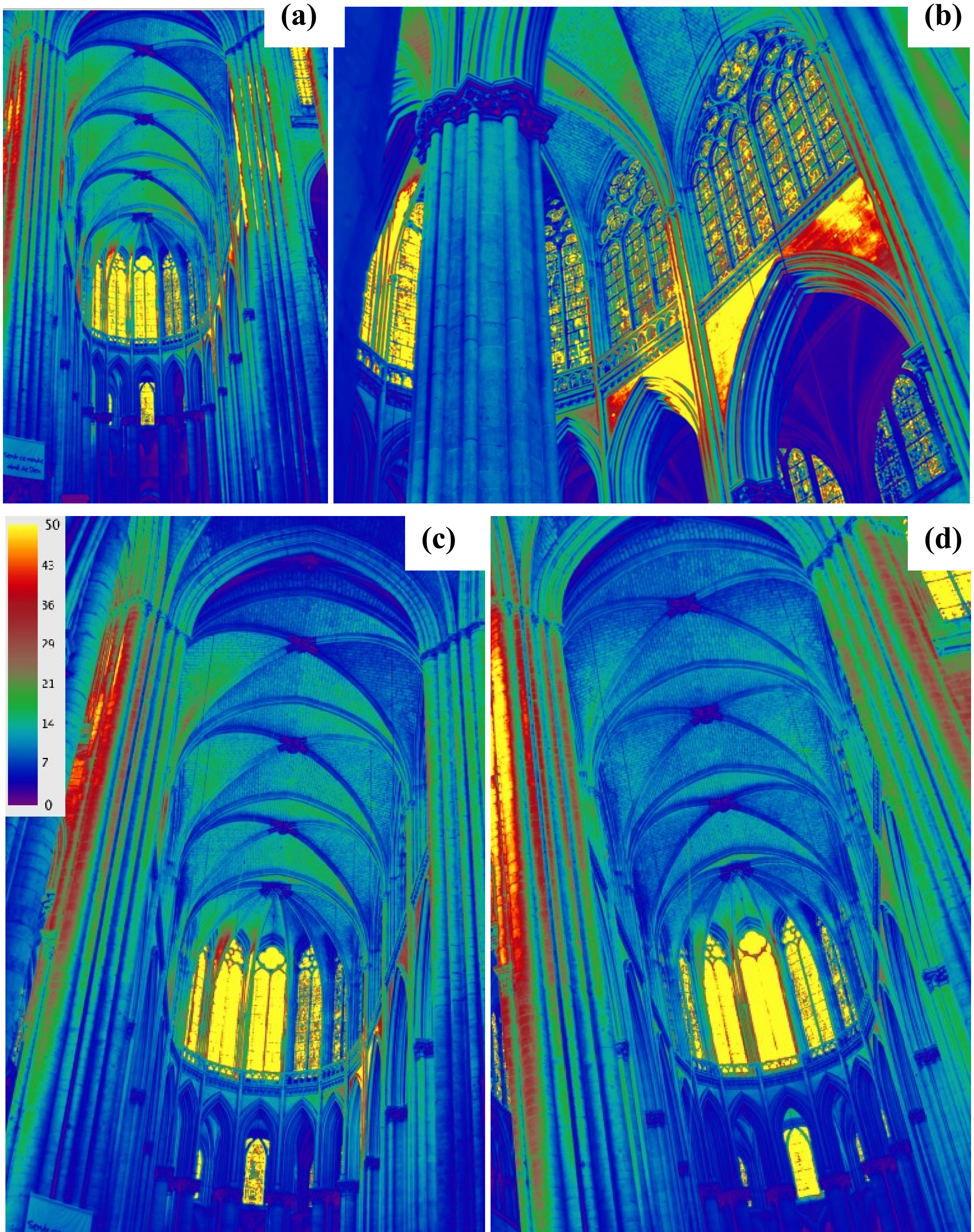


Figure 4.10: Luminance profiles (cd/m^2) for the choir of Le Mans Cathedral on the morning of 30 June, 2008, taken at (a) 718 GMT, (b) 747 GMT, (c) 805 GMT, and (d) 1007 GMT.

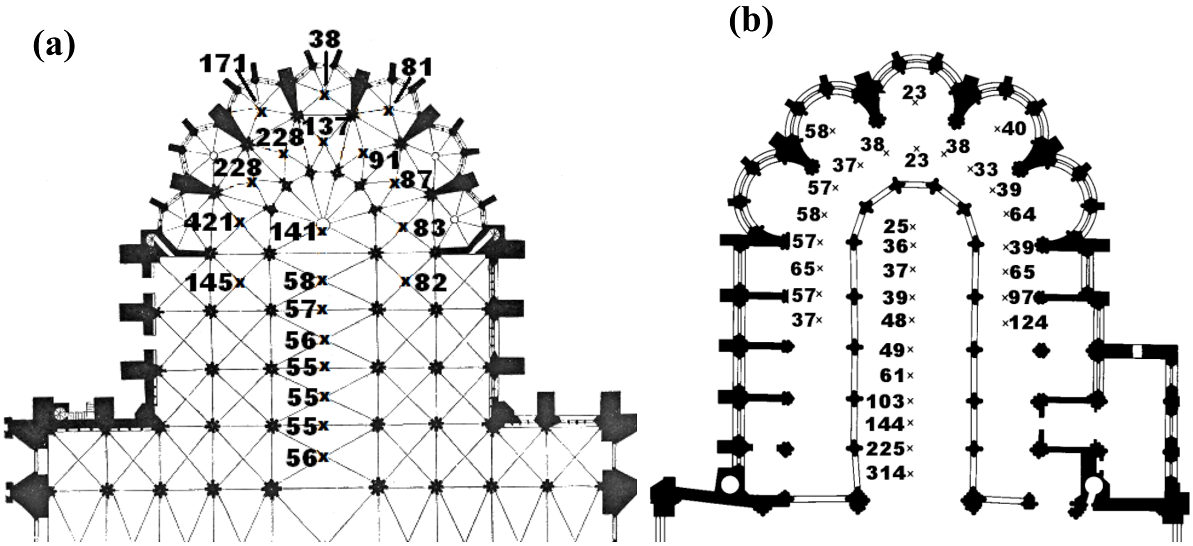


Figure 4.11: Horizontal daylight factors (multiplied by one thousand) in (a) Cologne Cathedral, based on one round of measurements, and in (b) Tours Cathedral, where the numbers are an average based on two rounds of highly precise measurements. The two figures are not on the same scale.

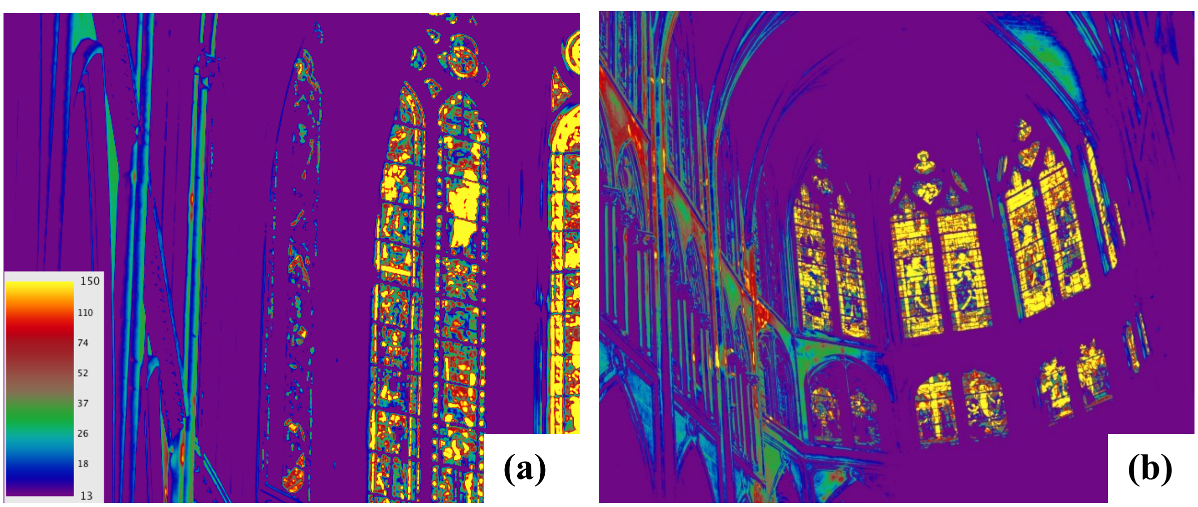


Figure 4.12: Clear sky luminance profiles (cd/m^2) of spandrels below clerestory in Le Mans (a) at 1347 GMT on 25 January, 2008, and in St-Serevin (b) at 1236 GMT on 23 January, 2008. The luminances at 25-42 cd/m^2 for the north-side spandrels of Le Mans were also confirmed in another HDR image taken in the south ambulatory (not shown).

Figure 4.13: The effects of solar illumination on the north clerestory windows of St-Serevin, Paris, with the obscuring effects of backlighting somewhat evident on the triforium windows and a few clerestory windows. Image taken on 23 January, 2008 at 1208 GMT.

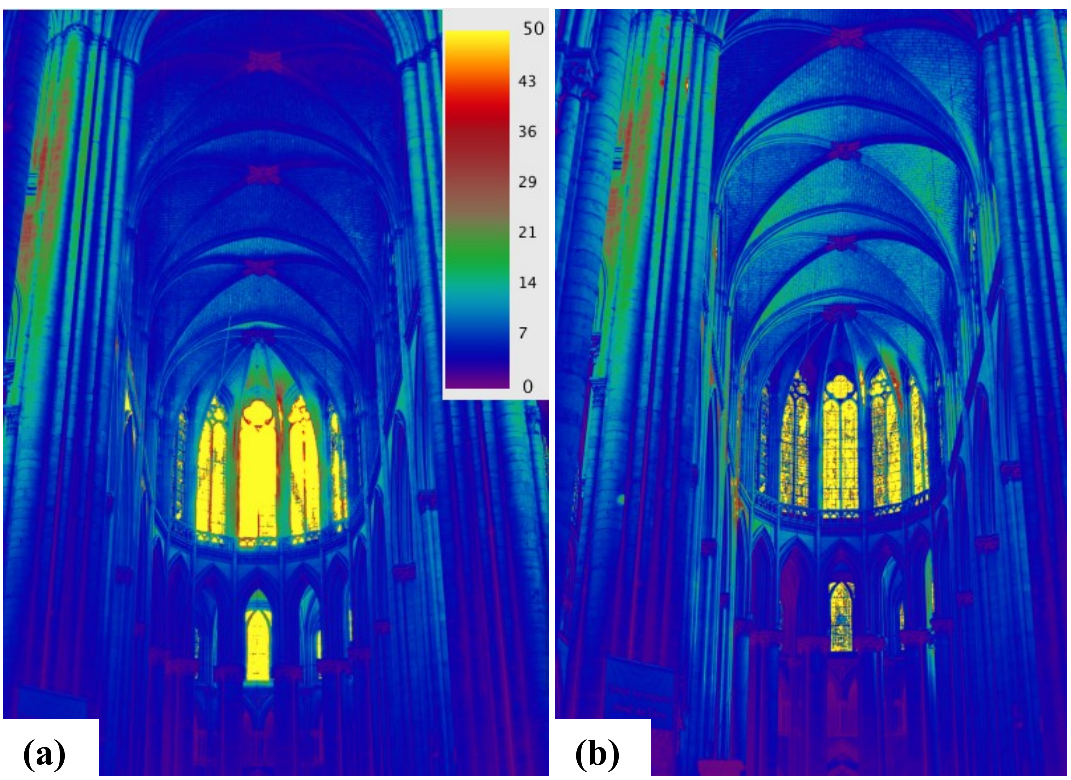


Figure 4.14: Clear sky luminance profiles (cd/m^2) of the choir of Le Mans Cathedral at (a) 1041 GMT on 25 January, 2008 and at (b) 1347 GMT on 25 January, 2008.

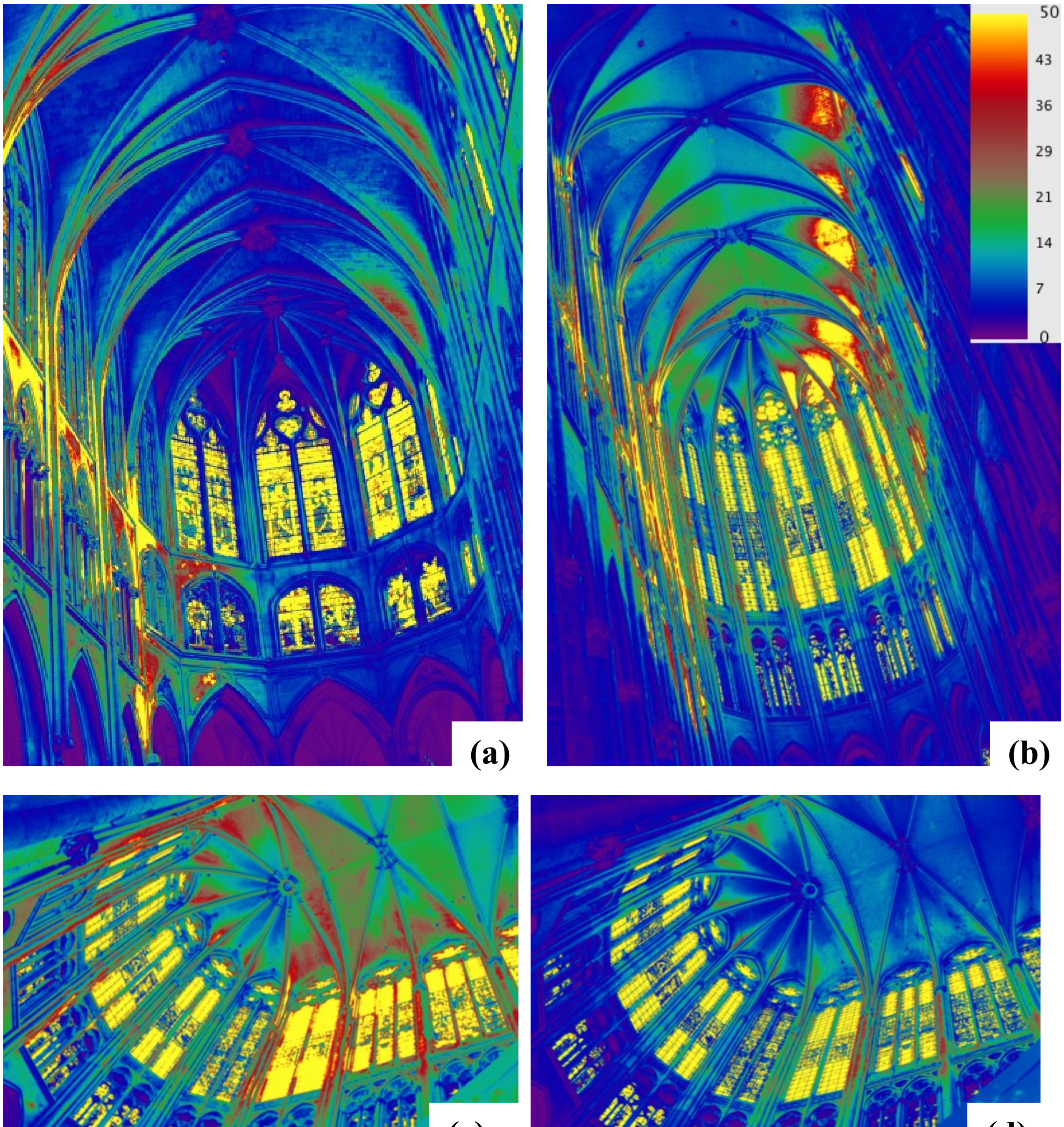


Figure 4.15: Clear sky luminance profiles (cd/m^2) of the choirs of (a) St-Serevin at 1236 GMT on 23 January, 2008 and (b) Beauvais Cathedral at 1055 GMT on 12 January, 2008. Beauvais Cathedral under partly cloudy skies on 16 June, 2008, is presented in (a) with sun fully exposed at 1400 GMT and (b) with stratocumulus overcast (mostly cloudy conditions) obscuring solar disk at 1406 GMT.

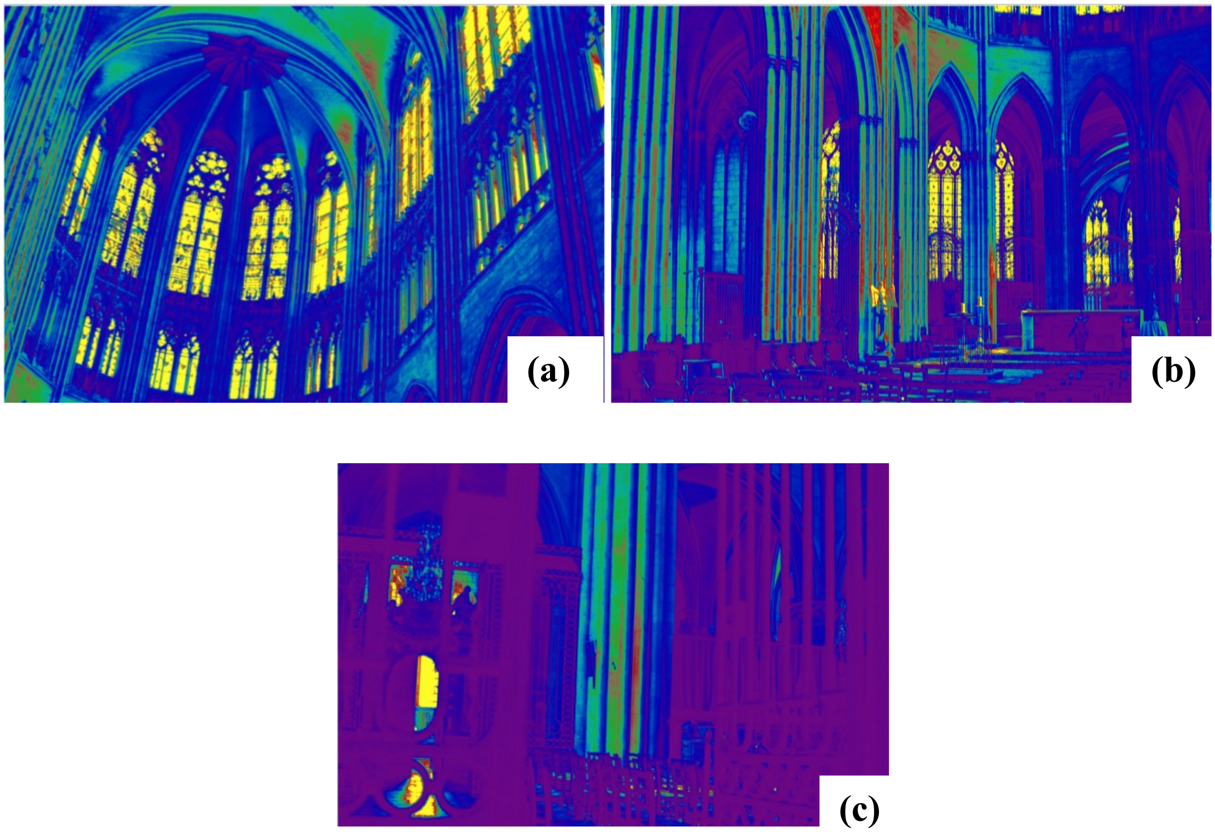


Figure 4.16: Clear sky luminance profile (cd/m^2, same scale as Figure 4.15) for (a) the choir clerestory of Évreux Cathedral at 1132 GMT on 24 June, 2008, (b) the lower choir of Évreux Cathedral at 1138 GMT on 24 June, 2008, and (c) the lower choir of Le Mans Cathedral at 1014 GMT on 30 June, 2008.

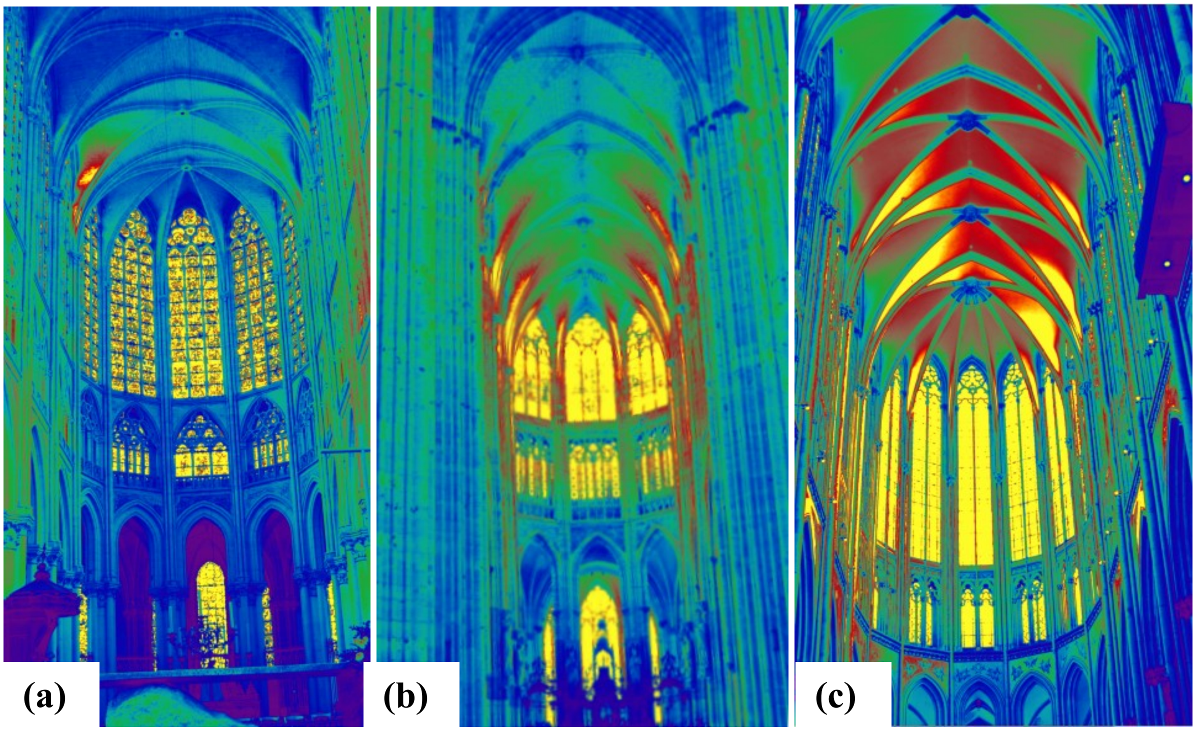


Figure 4.17: The choir overcast luminance profiles (cd/m^2) (in scale shown in Figure 4.18) of (a) Tours Cathedral at 955 GMT on 29 January, 2008, (b) St-Ouen in Rouen at 1051 GMT on 26 January, 2008, and (c) Cologne Cathedral at 1211 GMT on 14 January, 2008. In (c), luminance values have been multiplied by a factor of 0.76 to account for the higher reflectance of the white paint compared to the original limestone surface, assuming that the paint and limestone have a similar diffusivity.

(a) **(b)**

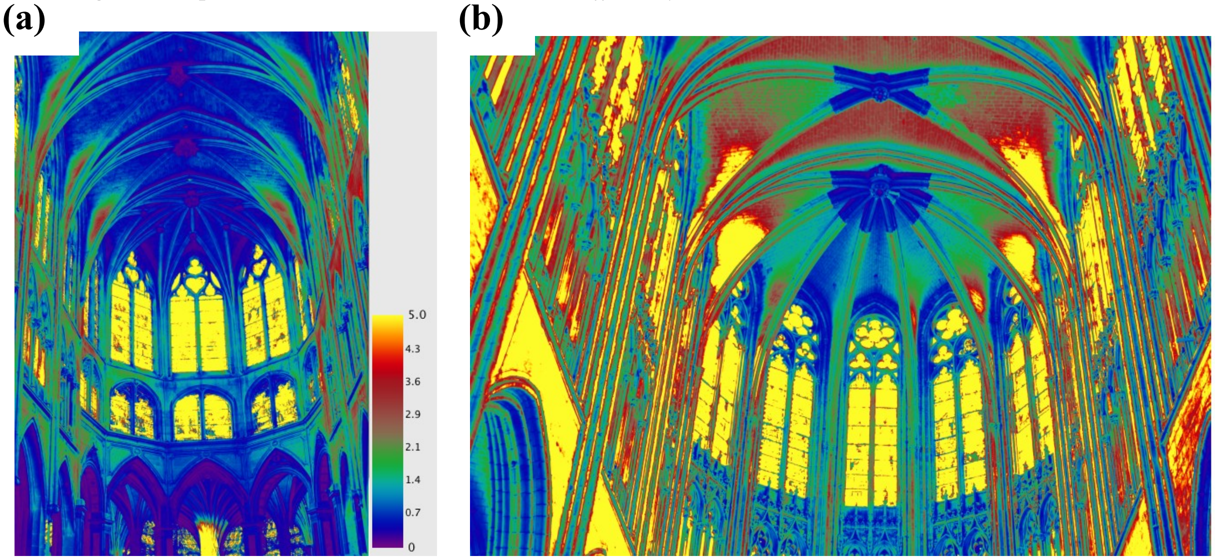


Figure 4.18: Luminance profile (cd/m^2) for (a) St-Serevin under overcast conditions, taken at 1046 GMT on 23 January, 2008 and for (b) Évreux Cathedral under overcast conditions, taken at 1037 GMT on 27 June, 2008.

(a) **(b)**

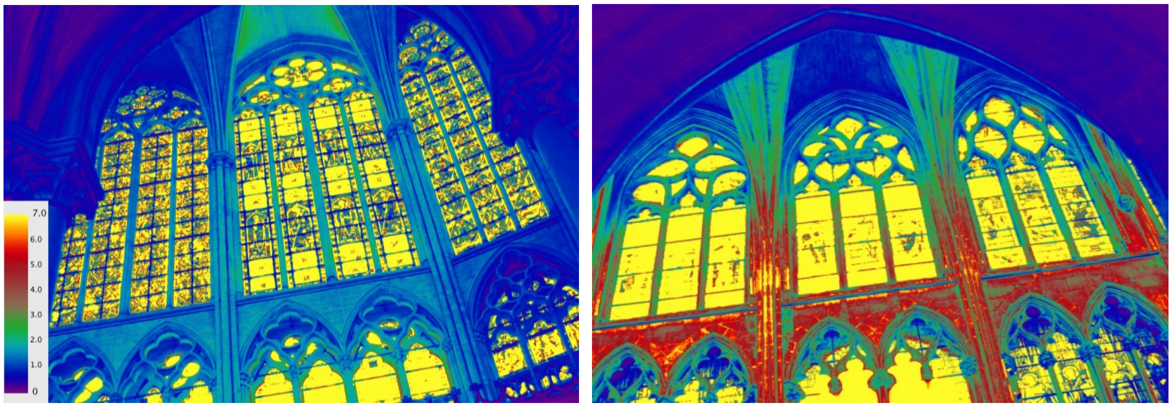


Figure 4.19: Spandrel luminance profiles (cd/m^2) under overcast conditions for (a) Tours Cathedral at 1024 GMT on 29 January, 2008 and (b) St-Serevin at 1100 GMT on 23 January, 2008.

Figure 4.20: The effects of backlighting on Cologne Cathedral's choir clerestory, taken on 30 April, 2007 at 812 GMT.

Figure 4.21: Winter backlighting (12 January, 2008) in Beauvais Cathedral taken at 1017 GMT in (a), and at 1434 GMT in (b).

Figure 4.22 : St Ouen eastern nave clerestory, 26 January, 2008, 1504 GMT.

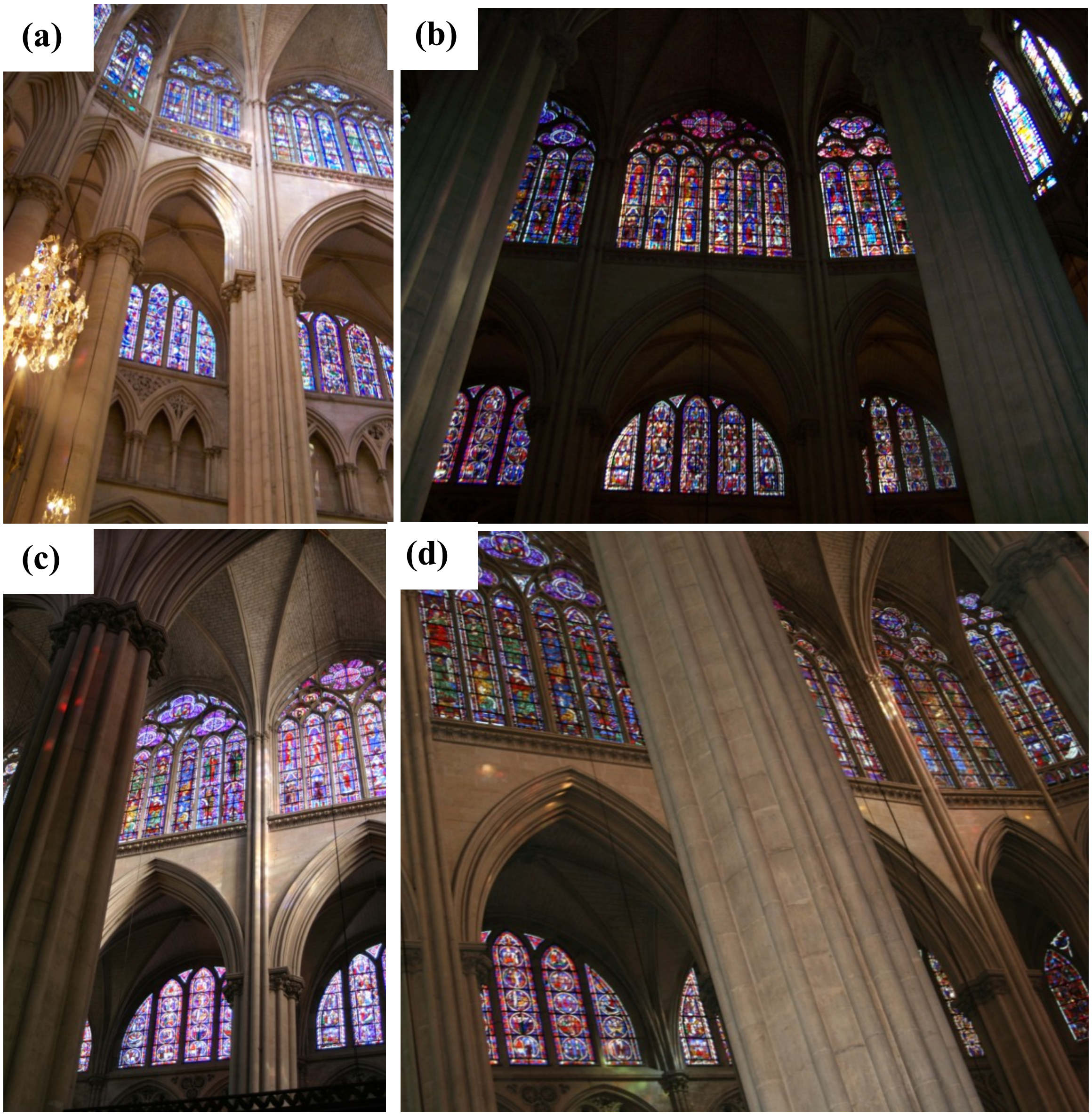


Figure 4.23: Backlighting in Le Mans interior. Panel (a), top left, taken on 3 June, 2007 at 734 GMT, demonstrates summer morning low sun angle backlighting. At a later time, in panel (b), top right, taken on 1 June, 2007, at 942 GMT, no backlighting is visible. In panel (c), bottom left, taken on 25 January, 2008 at 1026 GMT, the southeast choir clerestory is receiving the greatest direct solar radiation as in panel (b), but this time with backlighting visible. In panel (d), bottom right, taken on 25 January, 2008 at 1253 GMT, backlighting is visible on some of the side walls and in isolated patches on the windows.

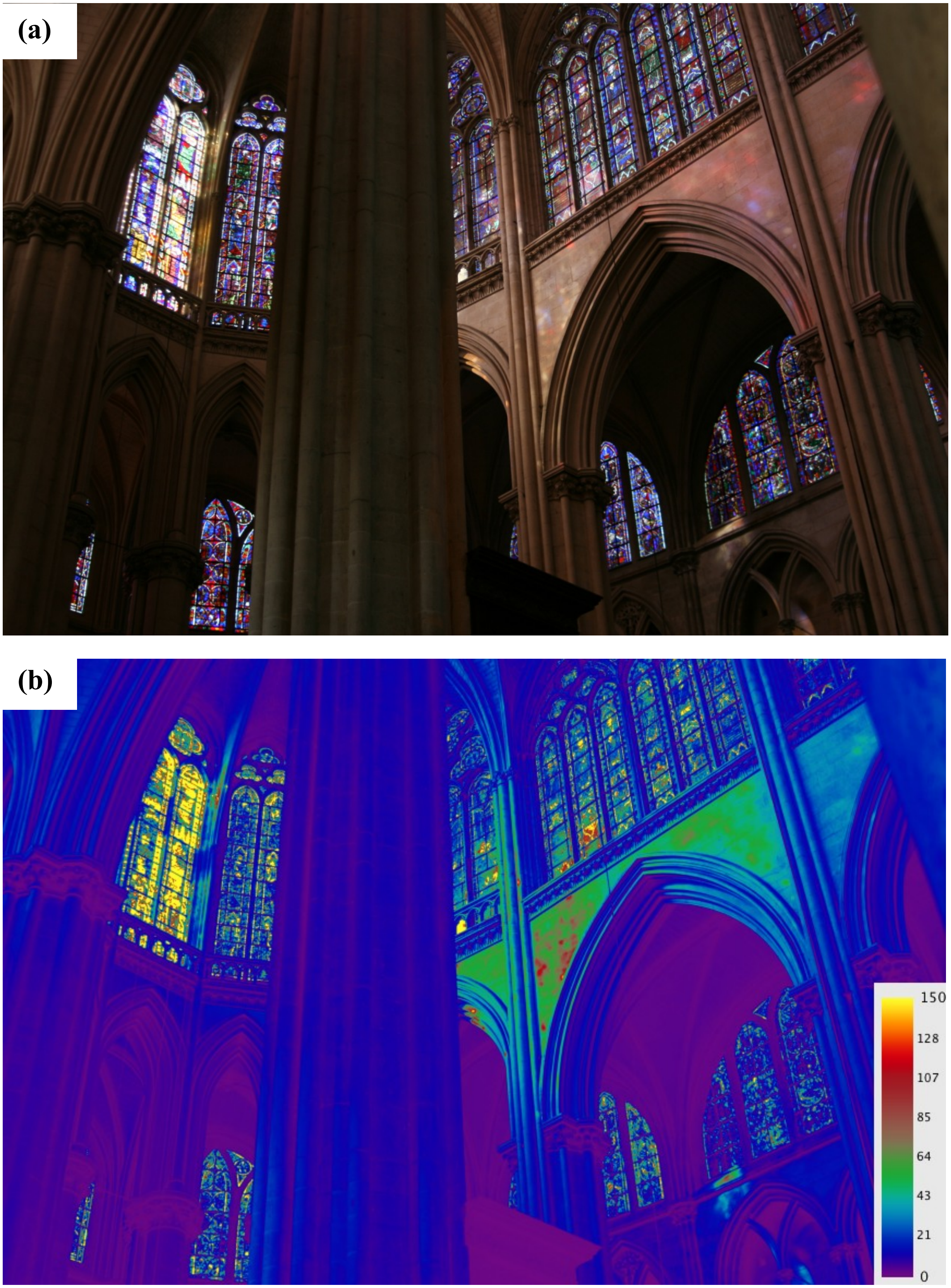


Figure 4.24: (a) photograph and (b) luminance profile (cd/m^2) of backlighting on Le Mans Cathedral's south clerestory windows, taken on 30 June, 2008 at 727 GMT.

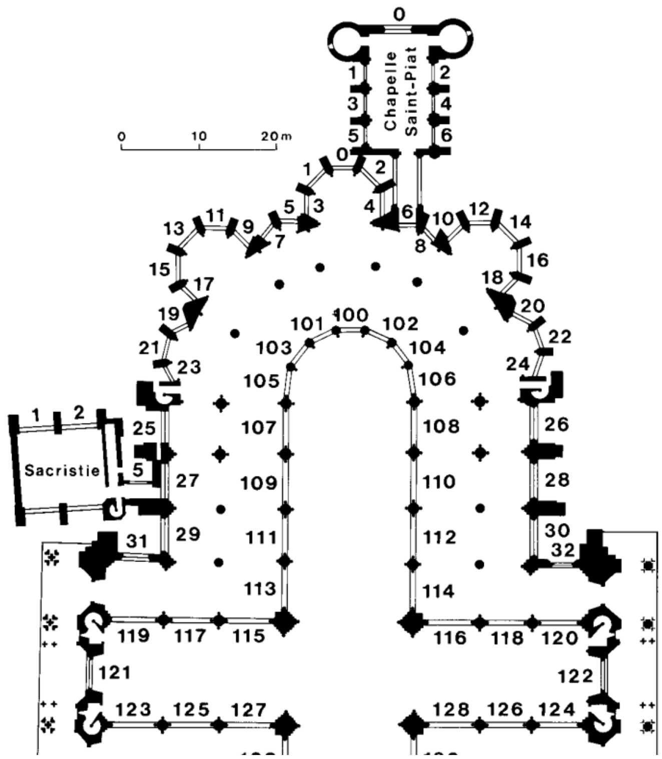


Figure 4.25: Plan of Chartres ambulatory and choir with window numbers, adapted from Grodecki et al. (1981).

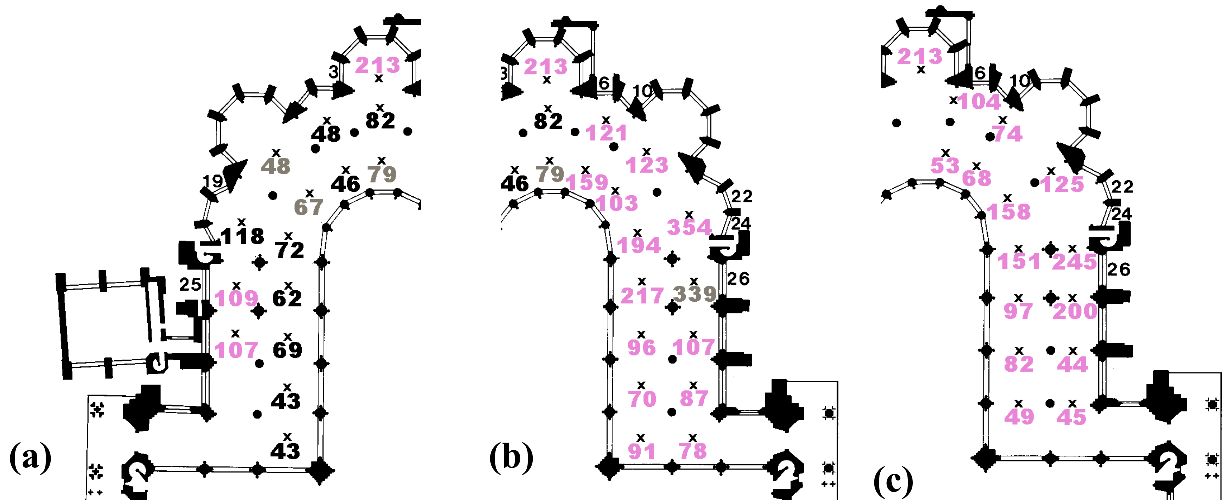


Figure 4.26: Daylight factors (multiplied by one thousand) in the ambulatory of Chartres, (a) for the north ambulatory and (b) and (c) for sections of the south ambulatory during two different rounds of measurements. Numbers shaded in black indicate a highly precise average (within 0.015% of both observations) of two daylight factor calculations. Medium grey represents averaged daylight factors that fall just outside of this precision range, and pink values represent calculated daylight factors based on only one round of observations. The windows associated with grisailles or otherwise white-dominated glass are numbered according to their bay number as represented in the Corpus Vitrearum Medii Aevi (Grodecki et al., 1981).

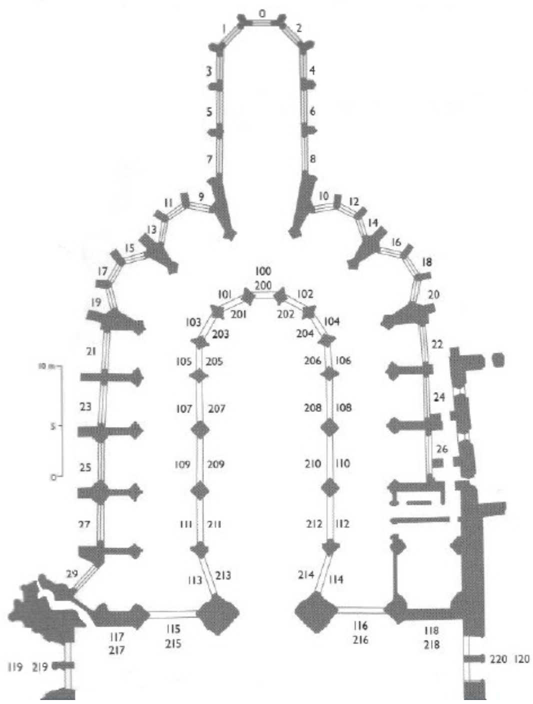


Figure 4.27: The ambulatory and choir of Notre-Dame-d'Évreux with window numbers, adapted from Callias Bay et al. (2001)

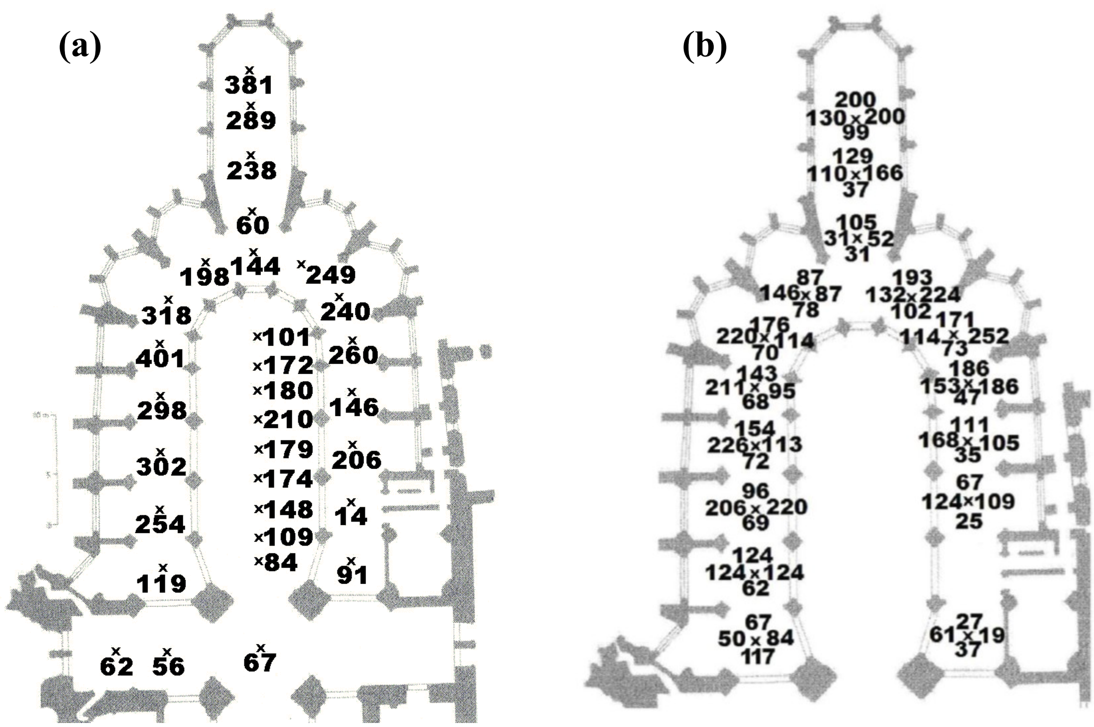


Figure 4.28: Horizontal daylight factors (multiplied by one thousand) are provided in (a), calculated from three rounds of measurements. Vertical daylight factors (multiplied by one thousand) are presented in (b) for the ambulatory at Évreux Cathedral, calculated based on one round of measurements.

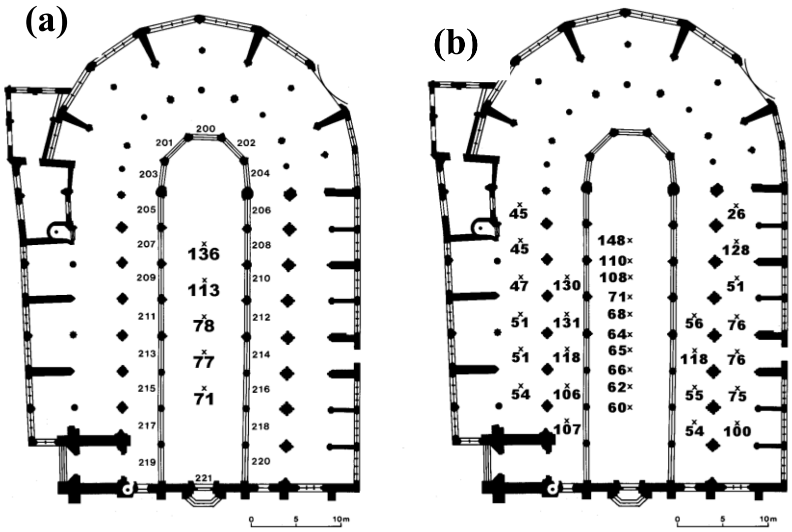


Figure 4.29: Horizontal daylight factors (multiplied by one thousand) for St-Serevin in Paris. In (a), the clerestory window numbers and high precision daylight factor averages are presented, and in (b) the daylight factors determined over the course of two rounds of winter measurements (the inner nave during one, all other points for the others) are given.

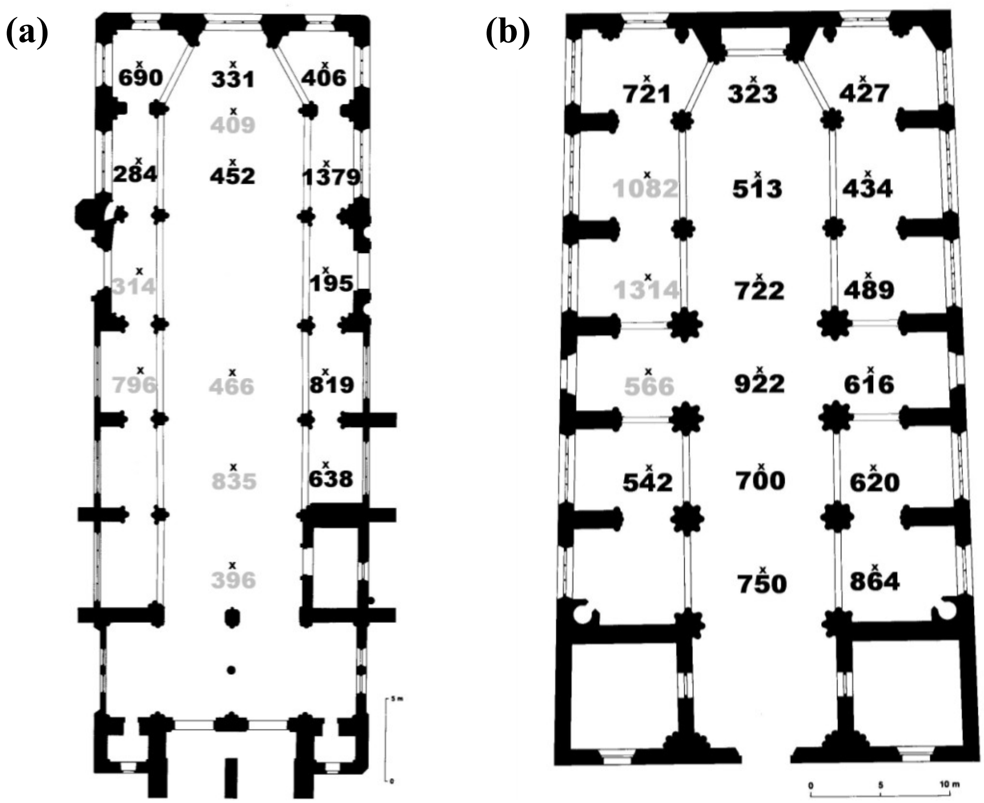


Figure 4.30: Horizontal daylight factors (multiplied by one thousand) for St-Nicolas (a) and St-Pantaléon (b). Averages of two calculated daylight factors are bolded in black, and daylight factors based on only one round of measurements are shaded light grey.

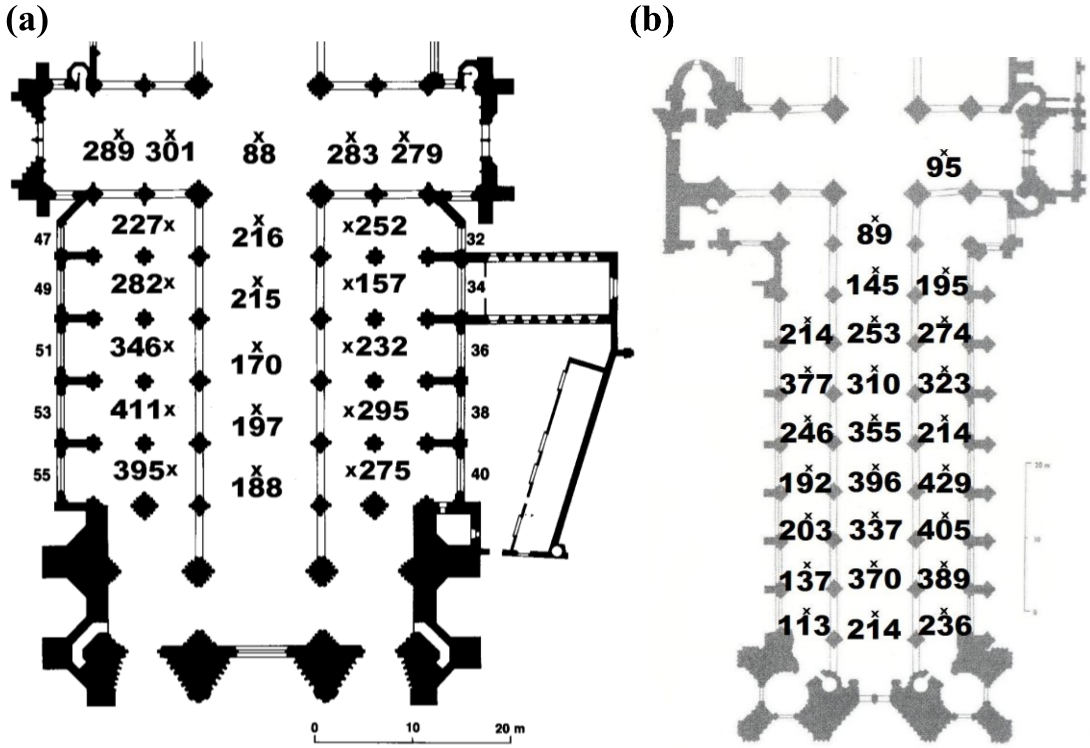


Figure 4.31: In (a), horizontal daylight factors (multiplied by one thousand) in Troyes Cathedral based on one round of measurements, with the window numbers of the side-aisle windows indicated. In (b) are presented horizontal daylight factors (multiplied by one thousand) in the nave and side aisles of St-Ouen in Rouen, based on one round of measurements.

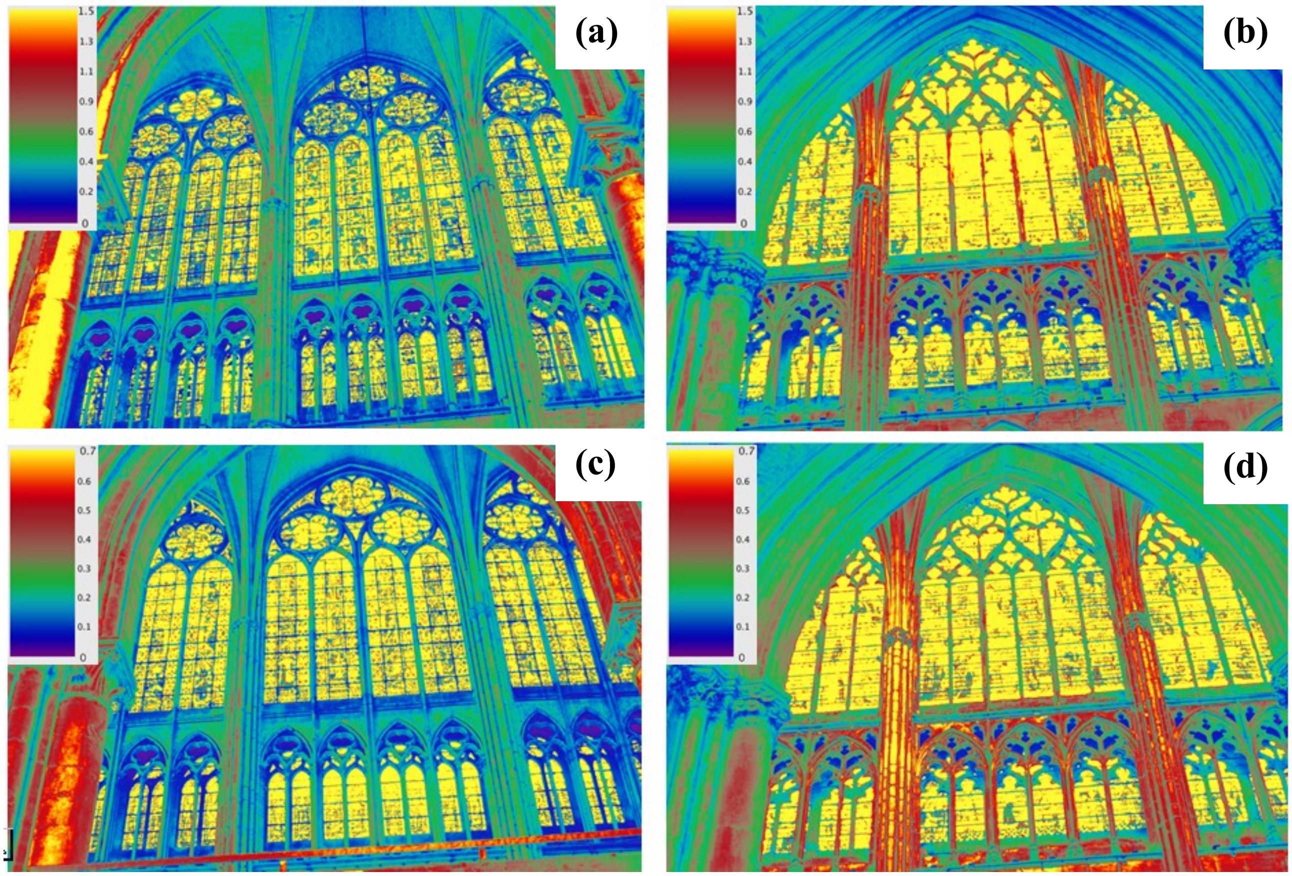


Figure 4.32: Luminance profiles (cd/m^2) obtained from four HDR images taken on 9 January, 2008 in the choir (a and c, top and bottom left respectively) and nave (b and d, top and bottom right respectively) of Troyes Cathedral. The window numbers are those provided in Grodecki et al. (1992). North choir HDR in (a), taken at a mean time of 1510 GMT, is centered on Window 209, whereas in the north nave (b) taken at a mean time of 1516 GMT, is centered on Window 232. In (c), the south choir HDR photo series, taken at a mean time of 1528 GMT, is centered on Window 208, whereas in (d) the south nave centered on Window 231 is taken at a mean time of 1533 GMT .

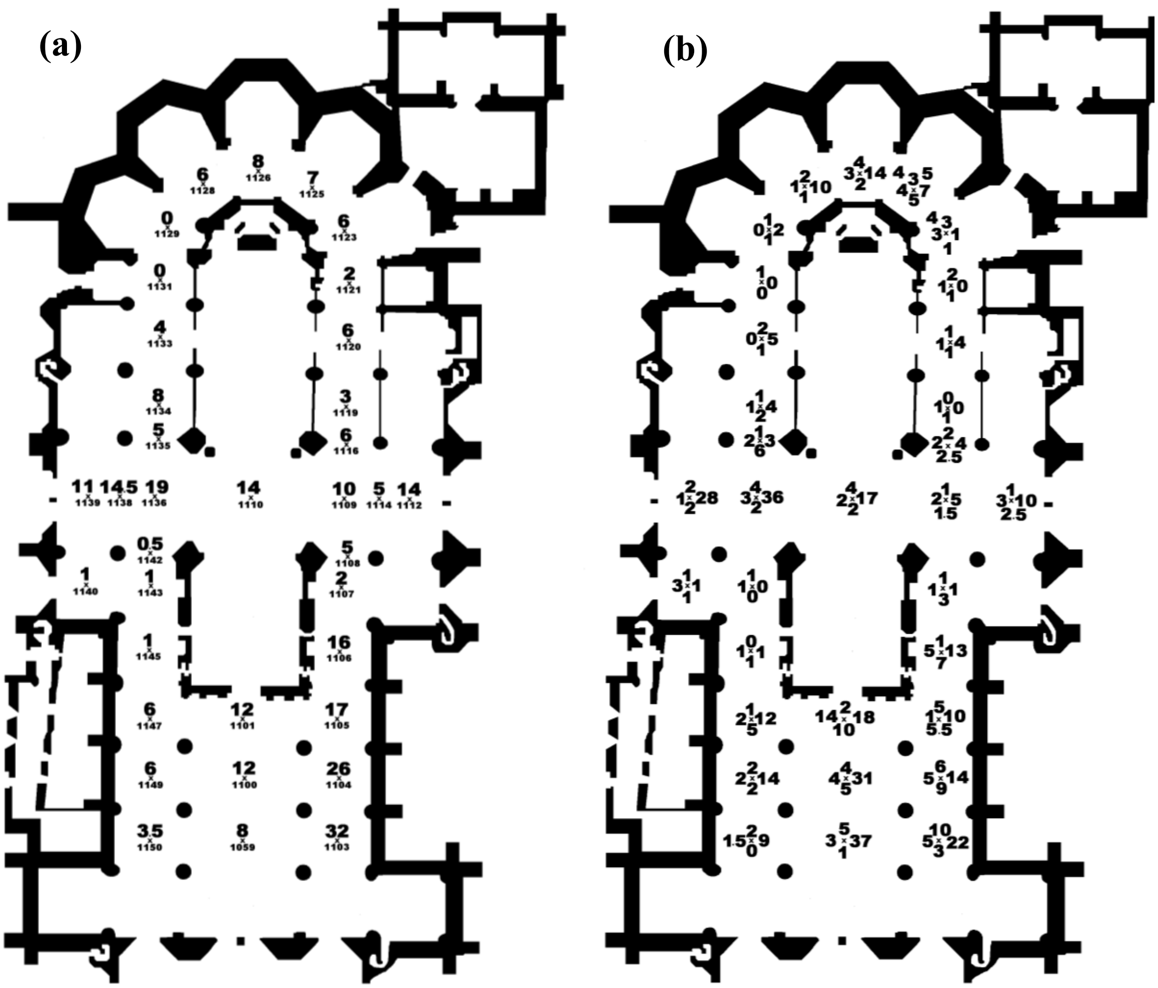


Figure 4.33: Illuminances (according to Instrument 4) under clear sky conditions in León Cathedral (in lux). In (a), horizontal illuminances at each indicated point are portrayed, with the time of the measurement (GMT) appearing below. The same times are valid in (b), where the vertical directional measurements are illustrated, with each value facing its respective direction.

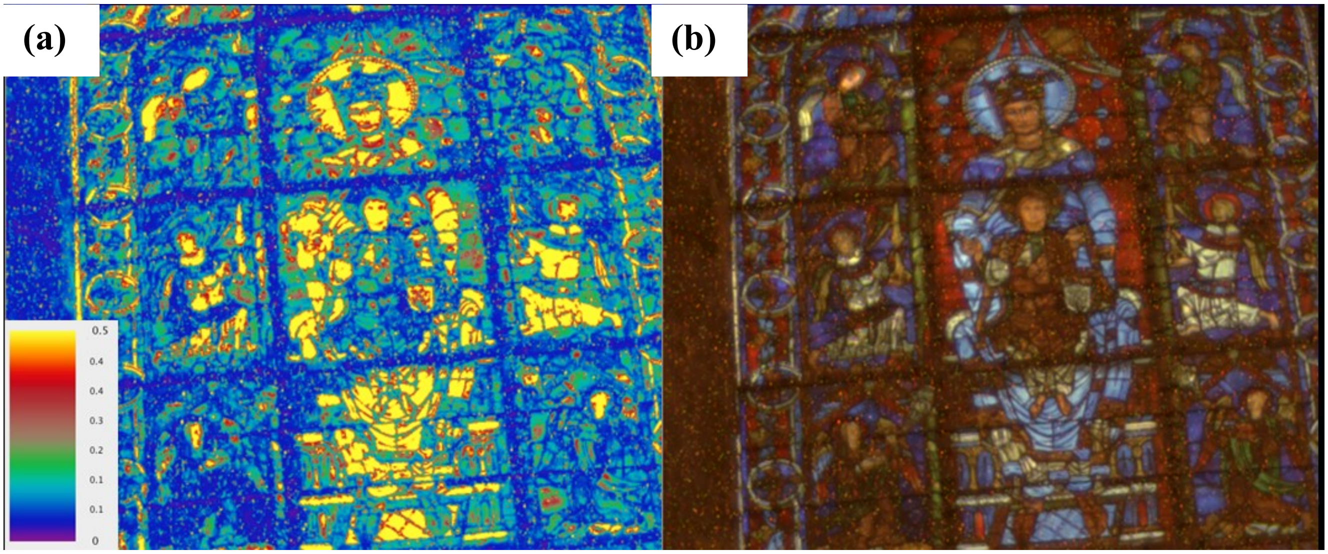


Figure 4.34: Notre-Dame-de-la-Belle-Verrière (Window 30) in Chartres Cathedral, with (a) a luminance profile (cd/m^2) of the window and (b) a colour photograph with the same view, taken under overcast conditions at 1526 GMT on 24 January, 2008.

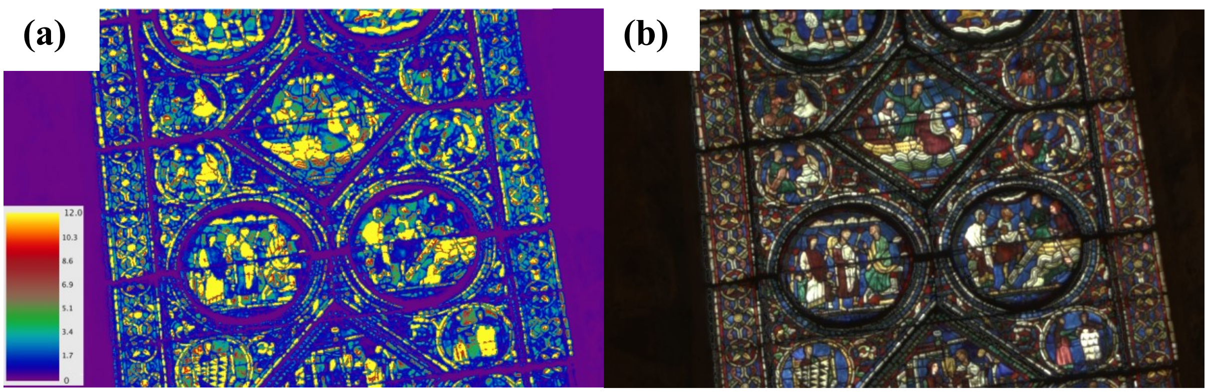


Figure 4.35: Luminance profile (cd/m^2) (a) and colour photograph (b) of thirteenth century glass in Window 43 in the north side aisle of Chartres Cathedral, taken at 1411 GMT on 24 January, 2008 under an overcast sky.

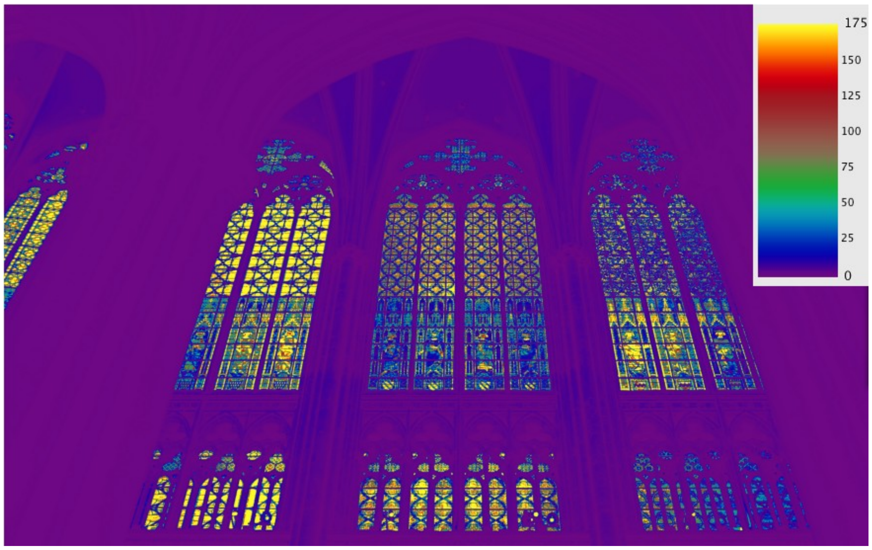


Figure 4.36: Luminance profile (cd/m^2) of Cologne Cathedral's south choir clerestory, centered on Window SVI, taken at 1316 GMT on 14 January, 2008 under overcast conditions.

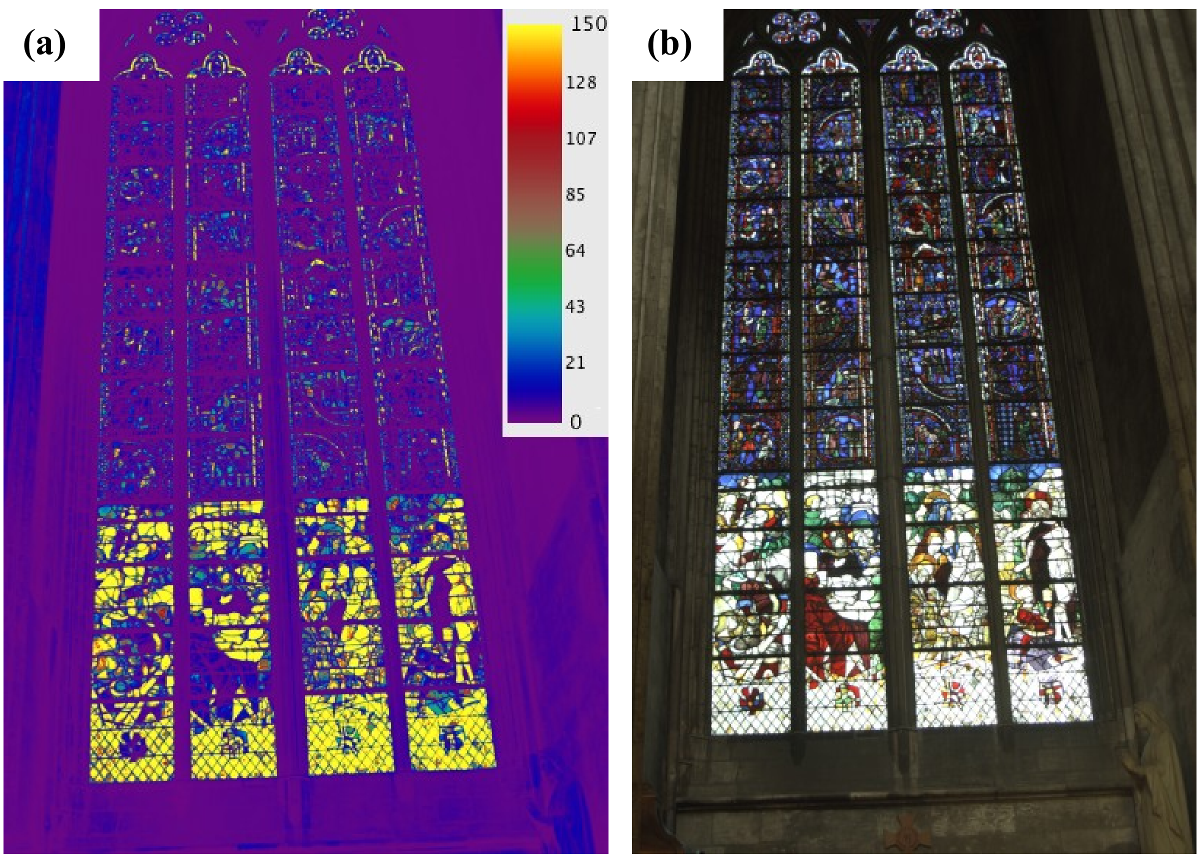


Figure 4.37: Luminance profile (cd/m^2) for Window 53 in Rouen Cathedral, taken at 1426 GMT on 26 January, 2008 under a clear sky.

Chapter 4 Tables

Table 4.1: Illuminance values taken using Instrument 2 in Bourges Cathedral under clear sky conditions in the spring and winter, based on location numbers in Figure 4.5.

Observations 25 May, 2008

Location	Time (GMT)	Horizontal	West	North	East	South
1	951	11	5	9	25	13
2	953	15	7	12	12	21
4	955	12	7	9	12	9
6	957	21	6	15	32	-
7	1000	31	8	24	57	-
9	1001	259	13	22	186	156
11	1002	53	12	21	82	36
12	1003	49	10	14	90	29
14	1005	45	13	11	84	48
17	1007	17	8	17	21	20
22	1009	7	2	8	11	11

Observations 22 January, 2008

Location	Time (GMT)	Horizontal	West	North	East	South
1	1040	32	23	24	45	43
2	1042	60	25	27	57	151
4	1204	37	-	-	-	70
6	1048	94	16	17	192	100
7	1051	49	23	18	68	60
9	1054	89	21	17	100	77
11	1159	43	-	-	-	78
12	1129	40	16	11	46	63
14	1131	30	16	6	67	75
17	1138	11	10	5	18	35
22	1152	19	18	11	9	39

Table 4.2: North ambulatory clear sky winter illuminance measurements in Bourges Cathedral using Instrument 2, based on location numbers in Figure 4.5.

Observations 22 January, 2008

Location	Time (GMT)	Horizontal	West	North	East	South
14	1131	30	16	6	67	75
15	1133	28	15	7	60	73
16	1136	12	13	4	8	27
17	1138	11	10	5	18	35
18	1142	9	-	-	-	-
19	1143	6	5	6	10	14
20	1146	6	4	7	7	11
21	1149	7	8	8	6	11
22	1152	19	18	11	9	39
23	1156	15	-	-	-	-
24	1158	17	32	11	8	42

Table 4.3: Illuminance Values (Instrument 1 for the 1 June, 2007 observations and Instrument 4 for the 25 January, 2008 and 30 June, 2008 measurements) in the interior of Le Mans Cathedral, based on location numbers in Figure 4.9

Observations 1 June, 2007

Location	Time	Horizontal	West	North	East	South	West (45º)	North (45º)	East (45º)	South (45º)
1	1237	44	26	15	20	23	-	-	-	-
2	1235	42	25	15	19	23	56	43	36	49
3	1240	41	25	9	23	26	-	-	-	-

Observations 25 January, 2008

Location	Time	Horizontal	West	North	East	South	West (45°)	North (45°)	East (45°)	South (45°)
1	1102	28	14	10	26	19	24	26	31	29
2	1103	29	15	10	18	15	26	27	28	29
3	1104	35	18	7	31	18	29	29	37	35

Observations 30 June, 2008

Location	Time	Horizontal	West	North	East	South	West (45º)	North (45º)	East (45º)	South (45º)
2	733	35	14	22	15	10	32	38	32	31
2	810	39	15	19	18	13	31	39	38	35
2	855	47	18	26	22	14	40	47	44	42
2	1018	73	18	14	32	14	48	66	73	66
3	1017	431	19	9	164	22	200	235	454	286

5 Conclusions and Future Work

5.1 Conclusions

Using an illuminance meter and luminance estimates determined from high dynamic range images, we have provided a profile of interior illumination in several Gothic churches and cathedrals retaining some proportion of their original stained glass. These measurements were performed during different seasons under different types of skies, with an emphasis on overcast versus mostly clear conditions. When possible, daylight factors or approximate daylight factors were calculated for overcast observations. These data, summarized in Table 5.1, indicate that the interior illumination in locations with lighting dominated by mosaic coloured glass (typical of early and mid-thirteenth century interiors in northern Europe) is extraordinarily low, with daylight factors ranging between 0.02% and 0.05% for most locations in Bourges, Chartres, Le Mans, Strasbourg, and Tours. Interiors with more grisaille windows and whiter glass from the late thirteenth century and fourteenth century, such as Cologne and Évreux, retain daylight factors that are nearly double (in the case of broader interiors such as the choir) or more than double (for ambulatory measurements). In addition, the coloured Renaissance programs of the fifteenth and sixteenth centuries (St-Serevin, Troyes) appear to provide similar daylight factors (generally above 0.1%), which are, like grisaille-dominated programs at Évreux, at times as much as an order of magnitude greater than the illumination in full-colour interiors.

The increase in ambient lighting in the white-glazed structures under overcast skies is enough to provide conditions that are nearly as bright (or as bright, depending on the season) as full-colour interiors under sunny conditions. The extremes between cloudy and sunny lighting are naturally more marked in the winter, when low sun angles provide much greater interior illumination in certain parts of the church under clear skies, whereas winter interior illuminances are very low under cloudy conditions. During the summer, exterior illuminances for cloudy skies are higher (horizontal exterior illuminances as high as 30000-40000 lux) for most overcast conditions than during the winter (horizontally rarely above 20000 lux), thus providing less of a contrast between solar and overcast lighting during the summer as seen in the winter. Therefore, changes in the winter cloud cover climatology (between the autumnal and vernal equinoxes) may have potentially more impact on how solar and diffuse interior lighting was perceived than under summer lighting. Therefore, if cloud cover (or lack thereof) was indeed a design factor, as suggested by Mediterranean and English glazing, winter cloudiness would likely be the most

important consideration. This is due to both climatologically greater cloud cover during the winter and the fact that winter illumination produces the greatest extremes between solar and overcast illumination lighting. Thus, the variability in cloud cover as it relates to the winter NAO is deemed pertinent to our study, and a significant transition in the NAO between the thirteenth and fourteenth centuries, associated with likely cloudier conditions over continental Europe, may be relevant to experimentation with glazing styles occurring simultaneously. Even though the lack of a lag between the grisaille revolution and the cloud cover changes may seem circumspect, the cloud cover shift may well have partially encouraged the development of high transmissivity quarries, the widespread adoption of silver stain, and the eventual conversion of German glass to more translucent glass in the fourteenth century. Furthermore, the climatic shift may have helped ensure continuity in the high translucency tradition throughout the fourteenth century.

As has been documented and established by various art and architectural historians, the increase in interior lighting associated with the grisaille revolution is readily observable with the human eye. Clearly, glazing transmission significantly affects how observers perceive the architectural space, and this concern has been incorporated into the existing theory on the motivations behind the grisaille revolution. We have addressed two of these motivations—formalist concerns and backlighting—in our study. Quantitatively the formalist argument (that grisailles intended to provide greater illumination to increasingly complex architectural forms) appears to be applicable only under certain conditions. For example, our luminance measurements suggest that solar interior illumination under full-colour interiors appears to provide an even illumination of the interior comparable to (in the case of Early Gothic programs such as St-Remi, Reims and Chartres Cathedral) or much brighter than (in the case of Rayonnant coloured programs) cloudy illumination for post grisaille-revolution interiors. Grisailled interiors also provide markedly greater form illumination to some surfaces in the interior under solar illumination, such as vault ribs adjacent to and other surfaces opposite windows receiving direct sunlight. However, despite these gains, much of the architectural space retains luminances equivalent to or only slightly greater than those seen in corresponding sections of full-colour interiors under sunny conditions. Furthermore, when provided with a clear sky and low sun angles (mornings, evenings, and all day during the winter months), backlighting becomes

particularly severe in white-dominated programs and often obscures windows opposite those receiving direct sunlight.

By contrast, under cloudy conditions, as demonstrated for Cologne and Troyes cathedrals, the illumination in grisaille revolution interiors becomes more even (as seen in Le Mans) and the luminance values seen on many of the architectural forms are as much as double or more those for full-colour interiors. The very nature of the overcast sky, with its largely symmetric luminance distribution, produces more substantial gains in lighting across the interior for post-grisaille revolution programs under cloudy conditions than those seen for sunny conditions when compared to coloured interior. Therefore, the formalist argument appears to be most applicable when evaluating the performance of full-colour and post-grisaille revolution interiors under cloudy conditions, and this suggests, along with the extensive and often debilitating backlighting seen for white-dominated interiors under sunny skies, that grisaille glass may have indeed partly served as an adaptation to cloudier conditions.

Furthermore, our research attempts to address some of the technological changes in stained glass production and its affects on glazing transmission (and, as a consequence, interior illumination). First, data from Rouen suggest that dark blue and red glass dating from the Renaissance does not provide a notable increase in transmissivity compared to mosaic glass from the thirteenth century. However, some colours, such as light green, light blue, yellow, and white, used in abundance in Renaissance works, together produce windows that transmit just under an order of magnitude more light than their thirteenth century counterparts. These results are broadly consistent with the increases in daylight factors seen between early thirteenth century programs and post-grisaille revolution interiors. In addition, our research suggests that, despite greater technological restrictions in the clarity of the glass, colour palette was used strategically (as suggested by Grodecki, 1983) during the Romanesque era. In particular, an analysis of Notre-Dame-de-la-Belle-Verrière in Chartres reveals that the light blue glazing of the robes of the virgin (a common colour, along with yellows and whites, used in surviving Romanesque glazing) is several times more translucent than the rich, deep blues chosen during the Gothic period when windows expanded. Thus, the rich, saturated full-colour glass of the thirteenth century was an aesthetic choice (rather than a technological constraint, as more translucent colour palettes were clearly possible), a wish for daylight illumination may have rendered the lighter tones of the Romanesque period more desirable, given smaller Romanesque apertures.

Therefore, despite the larger panes and increasing translucency possible for later glass, given the findings above we propose that the transmissivity and greater lighting of later eras was more of a deliberate human choice rather than the consequence of technological development. Aesthetically, this is suggested by the relative lack of white-and-yellow-dominated stained glass programs in the Mediterranean lands. In addition, the persistency of daylight factors between the grisaille revolution (with older grisaille glass) and later Renaissance programs also appear to support this claim.

Therefore, our conclusions remain that increasingly cloudy conditions over continental Europe during the thirteenth and fourteenth centuries may have influenced the aesthetic outlook and architectural design of many cathedrals, supporting the inclusion of more white glass during a period of remarkable experimentation in the design of these new temples of glass. While this study suggests that there is some correlation between the use of white glass and cloud cover variability, it does not conclude that cloud cover and cloud climatology changes are the primary driving factor in medieval stained glass aesthetics. Others, such as economic concerns, changes in religious philosophy (Lillich, 2000), and even broad, irrational trends in aesthetic tastes or perception may be equally or more important. In the latter case, the whiter light of the grisailled programs (and the quality of its illumination of various forms) may have come to be preferred over the reddish glow of many early programs, or light from white glass may have been perceived to make surfaces brighter. The contributions of other factors (as well as their limited ability to fully characterize the change in aesthetic) are discussed in more detail in Simmons (2007). Given the marked adaptations of architecture for even small changes in climate, as seen when comparing the more northern architecture of the Loire valley to that just a few hundred kilometers to the south, we do suspect that small changes in the climate system may be able to be seen in the way humans adapt to these changes. Therefore, the rapid transition occurring the Gothic period may have breached a threshold that required, either consciously or subconsciously, human concessions to the climate.

5.2 Prospects for Future Work in Cathedral Lighting

We have only touched upon the type of work that could be continued in documenting interior lighting in cathedrals. Often the scope of our research was limited by weather concerns, and more data will be needed and should be collected, if only for historical conservation purposes. For more information on interior lighting, measurements should be taken with several

types of light meters having different spectral sensitivities (as well as with calibrated luminance meters and HDR cameras), and in some cases a wavelength-specific analysis of the visible spectrum may provide more detailed information on properties of cathedral lighting. A series of light measurements may also be used to record changes in the quality of lighting both before and after the glazing or other interior surfaces undergo cleaning or a major restoration program. This may in turn provide us not only with an historical record of interior daylighting but also a quantitative measure of the effect of corrosive deposits on the transmission of daylight in the cathedral over time. Additionally, when certain windows are covered for restoration, a comparison of light measurements (both luminance and illuminance) taken before and during the restoration may indicate the contribution of light from one window or several windows to the whole interior lighting across the church. This would further define the detectable contribution of lighting from specific windows in the broader interior (for example, the contribution of a coloured mosaic window versus that of a Renaissance window).

In addition, we would like to see more work done in churches and cathedrals retaining stained glass that were not included in our operation (and there are hundreds). Due to geographic, time, and weather constraints, our best data is limited to a restricted region of northwestern continental Europe. Unfortunately, this project was not able to include English churches and cathedrals, and particularly well-maintained examples that our analysis of cathedral daylighting would profit from would include York Cathedral (and various city churches in York), Beauchamps Chapel, Lincoln's Inn Chapel, as well as luminance maps of particular sections of Wells, Salisbury, Lincoln, and Gloucester cathedrals, among others. Furthermore, data collected from a variety of well-preserved glazing in churches and cathedrals in Italy would shed further insight into Mediterranean illumination, such as in Assisi, Arezzo, and Venice. The translucency of alabaster in churches (e.g., Orvieto) should be investigated, and even Mediterranean churches with transparent windows would help provide an indication of the maximum possible lighting associated with particular window sizes and orientations. Comparisons of Mediterranean interiors to larger-aperture northern churches with both mostly modern glass, such as Amiens and Laon, and also those with structures retaining ancient glass (Chartres, Le Mans) may also be particularly instructive. These kinds of measurements help better clarify the lighting consequences of particular window space to wall space ratios in broad interiors with similar layouts. Furthermore, even in France our study could benefit from more

examples of Renaissance interiors, such as are available in additional city churches of Troyes (St-Martin), Rouen (St-Patrice), and Conches-en-Ouche (St-Foy). Furthermore, more work should be done in documenting interior illumination in baroque interiors with original glazing, representing the heart of the LIA. Initial work (Fontoynont, 1999) suggests that daylight factors are around 0.5%, comparable or slightly above post-grisaille revolution programs such as Évreux.

Reflectance standards should also be applied to more interiors, as they may be able to better clarify the capacity of the stonework to reflect in its current state (compared to how it would have likely reflected in its original form). Furthermore, we may be able to upward-adjust expected luminances (in a similar procedure as we downward-adjusted for painted white surfaces in Cologne) for surfaces that are particularly darkened; this has already been helpful in evaluating the original lighting in interiors such as Chartres, St-Serevin, and others. With a more surface reflectance-oriented analysis, the impact of blackening and patina on the interior illumination can thus be determined and erased from our measurements to present a more idealized picture of the cathedral during the Middle Ages.

In addition, average daylight factors may also be a useful measure of comparison. The current algorithm (see Li et al., 2006) is ideally suited for a single room, and thus the formula would have to be modified to take into account the complex geometry and multiple apertures of the interior. Then the same methods could be used to estimate daylighting in Romanesque churches with different types of glazing (waxed parchment, glass in style similar to Le Mans, grisailles, modern glass, etc.) to determine the degree of possible lighting in Romanesque churches. A much more robust approach, although potentially time-consuming, would be to model the interior illumination (luminances and illuminances) using a ray-tracer program such as Radiance (http://radsite.lbl.gov/radiance/). This could be achieved through constructing a particular cathedral, with all of its complexities, in Ecotect, simulating different lighting conditions using Radiance, and perhaps simulating different exterior lighting conditions using Daysim (to calculate Daylight Autonomy, among other metrics) (J. Veitch, Personal Communication, 2007). Such simulations would allow the modeller to fill the window apertures with different types of glazing (perhaps upward-adjusting according to the transmission we would have expected the windows to have had at the time, estimated from measurements of particularly well-preserved glass fragments). A test run would traditionally be performed to

reconstruct glazing transmissions as they exist under real world measurements to verify the performance of the model, and then the apertures could be assigned with transmissivities typical of coloured glass, grisaille glass, or modern glass to determine the limits of measurements of interior lighting (Beauvais could, for example, be filled entirely with coloured glass, and luminance profiles could provide an indication of any likely areas of backlighting). This would thus be particularly helpful in (1) reconstructing likely illumination in interiors where much of the original glazing has been destroyed, or (2) intended illumination when a program was never finished. In addition, the reflectivity and surface diffusivity of the materials could also be varied to determine the sensitivity of interior illumination to these parameters.

Beyond architectural lighting, more work could also be done in the climate sciences. For example, comparisons of Proctor et al. (2000) with the modern period could help establish NAO values, and cloud cover on years with similar NAO indices may provide a more quantitative cloud cover climatology estimate for the Middle Ages (a similar process could also be applied to the fourteenth and fifteenth centuries of the LIA). More cloud cover modelling over Europe may also help determine historical illumination patterns associated with a variable climate system, and this could be linked to the model of an interior to see the altered daylight metrics of a building under different climate regimes. These results may help further define quantitatively the degree to which the climate transition of the medieval period would have affected interior lighting. Furthermore, climatic sensitivity to the window size in particular could be evaluated by doing a more statistical analysis of windows sizes (and proportion of wall space) versus latitude, or including multiple variables (time, latitude, window size, and glazing transmission).

Finally, the art historical community may find some benefit from our methods. As previously mentioned light measurements may be able to record before and after changes associated with restoration and cleaning programs. In addition, the luminance measurements, with their ability to provide a measure of relative transmissivity, may be able to be used to quickly identify anachronistic replacement glass panels, much of which were not documented by the original restorers. Although glass has often been installed to appear similar to surrounding ancient panels, sometimes the translucency of glazing from the Renaissance eras through the nineteenth century is brighter than the original, worn glazing (as seen in the lancet heads in Figure 4.34a). For largely clean windows, an HDR false colour luminance image can be generated, and extreme luminances for specific colours may reveal the location of an

anachronistic panel. However, the exterior illumination conditions for which this methodology could be best applied has yet to be determined. In short, the prospects for future research in cathedral lighting, as part of the broader quest to understand the design and performance of these structures, is very bright.

Chapter 5 Tables

Table 5.1: A summary of illuminance data and daylight factors for a variety of churches and cathedrals. Upper limit indicates situations in which there is a substantial mixture of high-translucency modern glass affecting the interior lighting, thus defining the maximum lighting levels possible with a particular type of glazing.

	Horizontal Daylight Factors	Sunny Illuminances
Full-Colour Interiors	**0.02-0.05%** (Angers, Bourges, Chartres, Le Mans, Strasbourg, Tours)	**25-50 lux** (Le Mans Choir, summer and winter) **15-60 lux** (Bourges Ambulatory, summer and winter) **2-8 lux** (Chartres Nave, spring/summer) **15 lux** (Strasbourg Nave, spring) **8-30 lux** (León, Winter)
Grisaille Revolution Interiors	**0.05-0.06%** (Cologne Choir) **0.10-0.20%** (Évreux Choir) **0.10-0.17%** (Bourges Nave) **0.07-0.15%** (St-Serevin, Nave) **0.15-0.40%** (Évreux Ambulatory) **0.08-0.35%** (Chartres South Ambulatory)	**34 lux** (Beauvais Choir, summer) **45-54 lux** (St-Serevin Nave, winter) **39 lux** (Évreux Nave, summer)
Renaissance Interiors	**0.18-0.23%** (Troyes Nave) **0.16-0.25%** (Bourges Ambulatory Chapels) **0.20-0.40%** (Évreux Lady Chapel) **0.08-0.22%** (St-Gervais-St-Protais, Paris, Nave/S. Ambulatory) **0.10-0.20%** (St-Romain, Rouen, crossing and transepts) **0.33-0.43%** (St-Étienne-du-Mont Choir and Ambulatory, Paris) **0.20-0.45%** (St-Ouen Nave, upper limit) **0.30-1.00%** (St-Pantaléon and St-Nicolas, Troyes, upper limit)	**39 lux** (Troyes Nave, summer) **140-200 lux** (Bourges Ambulatory Chapels, winter) **80-202 lux** (St-Gervais-St-Protais Chapels, winter) **20-131 lux** (St-Gerv.-St-Prot. Nave/Choir, upper limit) **238 lux** (St-Nizier Choir, Troyes, upper limit)

Appendix I: Glossary of Architectural and Fenestration Terms

Ambulatory—a passageway extending around the choir, usually to allow circulation between the radiating chapels. See Figure I.1 below.

Aperture—an opening or piercing in the stonework of an architectural facade, often filled with glass or some other translucent material (synonymous with window).

Bay—can refer to a distinct architectural space surrounded on four sides by arches (in the text distinguished as an 'architectural bay') or in stained glass jargon as a window (not used as such in this text).

Chevet—a semicircular, apsidal end of a church, usually in reference to the structure defined by the choir apse and hemicycle.

Choir—located to the east of the nave, the choir houses the church singers and was usually separated by a choir screen. In this text the choir refers to the broader space within the chevet, from the hemicycle to the crossing. Sometimes this term can be vaguely used as a broader representation of the east end of the church. See Figure I.1 below.

CIE Sky Standards—a series of 15 typical luminance distribution profiles (given various characteristics of overhead cloud cover or atmospheric particle distribution) developed by Kittler et al. (1997) and adopted by the Commission International d'Éclairage.

Clerestory—refers to the upper level of a church or cathedral, extending from the triforium to the roof and almost always pierced by large windows. 'Clerestories' or 'clerestory windows' refer to the apertures. In architectural vocabulary, the term 'clerestory' refers to any window above head height, used for optimal deep penetration of illumination.

Contamination Lighting—refers in this text to any light that comes from a source that has an anomalous glazing transmission compared to the interior's original state (for example, modern white glass or excessive corrosion may modify the values that would have been obtained if measurements had been taken during the Middle Ages). Most frequently used when describing areas near a large source of contamination (for example, directly lit by a modern window).

Crossing—in this text this term refers to the space where the transept arms in the latin cross plan intersect the central (usually west-east) axis of the church. See Figure I.1 below.

Daylight Factor—a proportion that is always constant for a standard overcast sky with a symmetrical luminance distribution at a given interior location. It is the internal diffuse illumination evaluated horizontally (toward the ceiling/sky) divided by the diffuse external horizontal illumination, as evaluated from a location with a hemispherical view of the sky, multiplied by 100%. In the figures of this text, daylight factors are multiplied by one thousand.

Early Gothic—refers in this text to the Gothic style in the twelfth and early thirteenth centuries, covering chronologically the period from the Basilique St-Denis to Chartres.

Enamels—often refers to the black or brownish paint applied to the window surface to provide details and outlines to geometric designs and iconographical windows. During the Renaissance they were often thinly and liberally applied to the surface to provide more pictorial effects.

Grisaille—a term than can apply generally to white-coloured glass (usually with a grayish tint), but it is used most commonly to describe ornamental white-dominated glazing in the twelfth, thirteenth and first half of the fourteenth century. They are often decorated with geometric forms and provided with bosses of colour.

Grisaille Revolution—a term used exclusively in this text to differentiate stained glass programs that predate and post date the transition from largely full-colour windows to grisaille-dominated band windows and band window variants across much of northern continental Europe (generally between 1280 and 1330).

Gothic—an international architectural style that was frequently applied across Europe to both secular and sacred architecture from the thirteenth through sixteenth centuries. It was first conceptualized and promulgated in Île-de-France during the 1130s-1140s as the 'New Style.' The gothic architectural style emphasizes the verticality of forms through pointed-arch vaults, arches, and windows, and the use of new forms of buttressing allowed gothic churches to attain heights and window sizes never seen before.

Flashed Glass—also called abrasion glass, is produced when a thin layer of one colour is adhered to another (most frequently with white glass). Red glass had to be flashed to white glass from its inception, and the technique was applied more rigorously in the fifteenth and sixteenth centuries due to the ability to scratch out details and colour variations.

Hemicycle—a semicircular or semipolygonal arc of clerestory windows, most frequently in the eastern apse or choir of a church or cathedral. See Figure I.1 below.

High Dynamic Range (HDR)—a method of capturing images so that there is a greater range of luminances and colours available for light and dark pixels (usually through multiple exposures, varying either exposure time or aperture size, or through the use of a specially calibrated HDR camera). Used in architectural lighting studies to produce estimated luminance false-colour images.

Illuminance—the luminous flux (visible light from all directions per second) received over a surface (measured in footcandles or lux), evaluated through the application of an illuminance meter.

Lady Chapel—refers to the chapel radiating off the ambulatory aligned with the central axis of the church, often larger than other radiating chapels for Rayonnant and Late Gothic interiors. It was frequently assigned special importance and as thus dedicated to the Virgin. See Figure I.1 below.

Late Gothic—generally includes architectural styles from 1300-1600 across northern Europe. In France, the Late Gothic period starts with late Rayonnant works and continues into the

Flamboyant period in architecture, distinguished for its elaborate tracery. In England, Late Gothic includes late Decorated and Perpendicular-style Gothic architecture.

Luminance—the luminous intensity (visible light emitted in a single direction per second) from a given source area. Measured in cd/m^2 and obtained through the application of a luminance meter and/or HDR capture.

Mosaic Glass—a form of window glazing in which small strips of glass are cut and welded together using lead cames, usually in reference to coloured glazing in the thirteenth century.

Narthex—an entry hall into a church, preceding the inner sanctum (a space separating the west front and the nave proper). See Figure I.1 below.

Nave—the central gallery of the church crowned by tall vaults; in a latin cross plan it refers to the central aisle between the west front and the crossing (or before reaching the altar/choir if a clear crossing is not present). The nave is usually separated from surrounding side aisles by tall, massive piers and looks directly into the choir in most French Gothic churches. See Figure I.1 below.

Rayonnant—(from the French, radiating) refers to the Gothic architectural style in northern continental Europe between 1240 and 1350, including interiors such as Amiens, Beauvais, Cologne, Tours, and Troyes (choir).

Romanesque—an international architectural style (although identified as such only in the nineteenth century) characteristic of buildings constructed in the eleventh and twelfth centuries (and well into the thirteenth century in some parts of Europe, such as the Holy Roman Empire). It is often characterized by semicircular archways and windows, half-barrel vaults, and the increasingly widespread use of ambulatories and radiating chapels in larger structures.

Side Aisles—aisles that are adjacent to and aligned with the central nave, usually possessing a markedly lower vault height (and overhead roof) than the central nave. They may provide access to peripheral chapels. See Figure I.1 below.

Silver (Yellow) Stain—a method of using silver or silver oxide to stain white glass various shades of yellow or orange (or blue glass green). Widespread use of silver stain techniques in stain glass started in the first decades of the fourteenth century and afforded the production of high translucency yellow glass.

Spandrel—the wallspace present between the two arches in an arcade.

Transept—in the latin cross plan, the transept refers to the two radiating arms of structure away from the central (usually west-east) axis of the church. The transepts are thus usually labeled north and south respectively. See Figure I.1 below.

Triforium—the middle levels of a church, usually elevated above the aisle-level window and below the clerestory, often accompanied by a tribune gallery. A pierced triforium refers to a triforium provided with apertures, particularly common by the Rayonnant period in architecture.

Tympanum—the upper portion of an entablature enclosed by an arch. It can refer to a stone slab above a portal or the pointed-arch section of a lancet.

Vault Boss (Key)—the location of the intersection of transept vault ribs, usually at the approximate centre of an architectural bay above the elevation of the framing arcade.

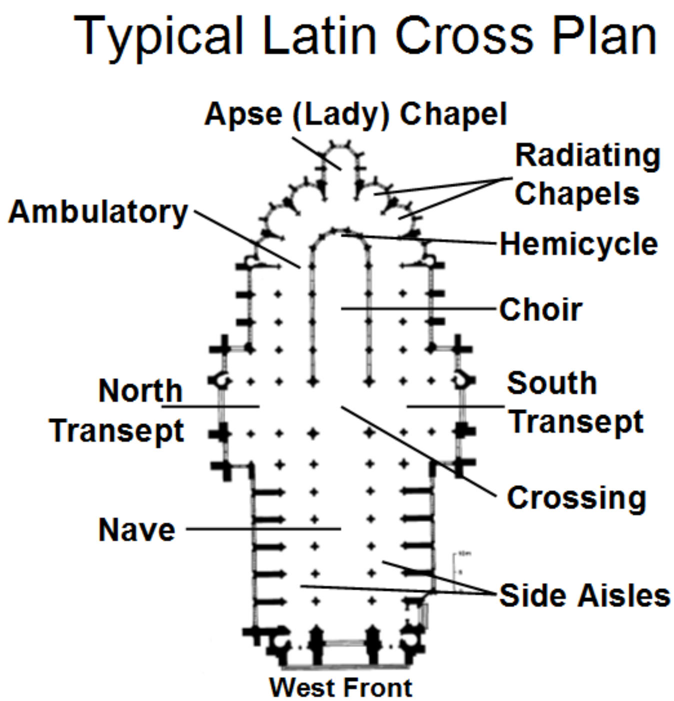


Figure I.1 Amiens Cathedral plan, adapted from Grodecki et al. (1978).

Appendix II: Instrumentation

We employed Extech 407026-model illuminance meters for our experiments; these were selected due to limited funding and the relatively low cost of these particular instruments. With a variety of options for different illuminance meters available, the balance between affordability and data quality was a delicate one, and the matter of the Extech 407026 model's suitability for the project design was presented before a meeting (March, 2007) at the National Research Council of Canada's Interior Lighting and Construction division in Ottawa. A general approval with respect to the instruments was given, but a few major drawbacks associated with the Extech 407026 model were identified. In particular, this instrument does not have the ability to resolve lighting levels at a resolution less than 1 lux in its low range (0-1999 lux), 10 lux in the middle range (1800-19990 lux), and 100 lux in the high range (18000-100000 lux).

Another problem with the instrument is a particular design flaw in which a relatively small, black plastic ring around the sensor exceeds the elevation of the sensor itself (when placed horizontally upright), thus cutting off any light incoming from directions greater than 80º from zenith. By contrast, most instruments possess such a ring at the same level as the actual light sensor in order to ensure cosine correction (so that light coming in at 90º with respect to the zenith as seen by the sensor does not reach the sensor, but incoming light at smaller angles can be read). If the greatest lighting does not occur at or near zenith with respect to the instrument sensor, then the ring has the effect of casting a small shadow over part of the sensor shield, which may further negatively affect values. However, the elevated ring blocking light from low angles worked to our advantage in taking exterior measurements in some cases, as exterior lighting values from locations with hemispherical and only quasi-hemispherical views would possess similar values. Thus, we were allowed greater leverage in choosing locations to take horizontal exterior measurements for the calculation of daylight factors. Because the ring was constant with time, a correction factor could be applied later to the data (similar to the exterior daylight factor verification described below) for the underestimation of total illuminance in these measurements. These factors likely provide errors that exist on top of those already typically associated with radiation instrumentation, such as cosine correction, thermal effects, nonlinearity, spectral selectivity and azimuthal errors, which together provide an estimated accuracy of +/- 4% with an additional +/- 2 digits in the low range (which could provide very large errors at the bottom end of

the low range). In order to better understand the totality of these errors, we took instruments 1 and 2 to the National Research Council of Canada to be tested.

II.1 Recalibration and Instrument Comparison

II.1.1 Lamp Experiments

Early during the first round of data collections in Europe in Spring 2007, the two equivalent Extech 407026 instruments appeared to show different values for similar lighting conditions, and thus they were labeled respectively as Instrument 1 and Instrument 2. The data were subsequently recorded with the instrument number and range in order to allow for further evaluation of the data. Because both instruments were often used in simultaneous measurements in the interior or exterior of churches, the use of just one instrument throughout the research mission was not possible. Another complicating factor centers around the fact that the two instruments appeared to have different sensitivities at the same corresponding ranges (low range, middle range, and high range values); in particular, Instrument 2's high range seemed to be sensitive only to lighting in shade or cloudy conditions, whereas Instrument 1's high range appeared to be most sensitive to full sun conditions and light overcast. In addition, Instrument 1 in the low range seemed to be markedly higher than Instrument 2 in the low range for the same measurement in some church interiors. However, all instruments appeared to give values that covaried with lighting conditions, with readings decreasing for lower illumination levels and increasing for greater illumination. Therefore, in order to understand the meaning of the instrumentation values and account for any broader data discrepancies associated with these light meters, we took both instruments to the National Research Council (NRC) of Canada in Ottawa, Ontario in September, 2007 to compare values given by Extech 407026 instruments 1 and 2 with those given by other calibrated light meters.

The standard for comparison was an illuminance meter developed by LI-COR Biosciences, comprising of an LI-250 (reader display) with a LI-210 SA sensor, with total accuracy (verified by the NRCC) being +/-5% sensor error and +/-0.4% and +/-3 significant digits reader error. A standard lamp calibration session in a room surrounded with black felt was graciously conducted by Chantal Arsenault (NRCC) in order to assess the values provided by the Extech Instruments. Lamp voltage was adjusted to 260.026 mV, which provides a reading of approximately 400 lux at a position of 1.0944 meters away from the light source along the lamp's axis. However, the estimated lamp error is approximately 2.3%, due in part to the alternating current of the electrical

source. The actual reading at this position as given by the LI-250A meter was 393.9 lux, whereas Instrument 2 yielded 395 lux and Instrument 1 yielded 402 lux in the low range. In order to evaluate if the instruments' values diverge more substantially at lower lighting levels, a neutral density 1 filter was placed over the lamp to reduce the lighting equally at all wavelengths by a multiplication factor of 10. This yielded a LI-COR value of 40.8 lux, an Instrument 1 value of 45 lux, and an Instrument 2 value of 43 lux. Thus, both instruments appeared to be reasonably close to the accepted value provided by the LI-COR meters. Similarly, when a neutral density 0.6 filter was added to the neutral density 1 filter to better simulate the extremely low lighting conditions found in many Thirteenth century churches, the 9.8 lux reading given by the LI-COR meter was very similar to the 10 lux of Instrument 2 and 11 lux of Instrument 1. Therefore, both Extech meters under the lamp conditions performed very well, even under very low lighting conditions, and Instrument 1 was consistently above Instrument 2 (although not to a substantial degree).

However, high performance under typical lamp conditions may not accurately represent the interior lighting of cathedrals, in which the light is filtered by windows with a large proportion of red and blue glass (this is especially the case for early Thirteenth century interiors). Because the spectral sensitivity of the meters is concentrated at green and lower for blue and red wavelengths, some of the divergence between the two meters might have been associated with greater errors when resolving light at wavelengths not within the meter's range of high spectral sensitivity. In order to test this possibility, we applied a primary red 106 filter to a neutral density 1 filter to create a spectrum of red wavelengths, and the resulting readings were similar to those under the full spectrum, with values of 5.1 lux for the LI-COR meter, 6 lux for Instrument 2, and 7 lux for Instrument 1. Thus, even within a limited part of the visible spectrum, the Extech meters displayed a reasonable accuracy and did not diverge strongly from each other.

In addition to analyzing spectral sensitivity, another experiment was designed with the intention of determining if light coming in at different angles may be evaluated differently between the two meters, considering that most light received by the meters in horizontally-placed measurements in churches was composed of direct light from windows to the side of the sensor rather than from direct reflections from the ceiling. The meters were rotated approximately 60-70 degrees away from zenith with respect to the lamp light source (covered by a neutral density 1 filter), and both gave similar readings: 8 lux for Instrument 1 and 7 lux for Instrument 2. In general, this and other lamp experiments reveal that both Extech instruments 1 and 2 perform with

reasonable accuracy at the low range under lamp conditions and do not appear to diverge significantly from one another in a variety of circumstances, although Instrument 1 gives consistently higher values than Instrument 2. It is important to note, however, that the instruments were also calibrated under lamp conditions (as indicated by the company calibration procedure document, provided to us), and thus high performance under these conditions is not unexpected. Few opportunities were available to test low lighting conditions extending from a more natural setting; however, one reading revealed that instrument 1 was approximately 1 lux under the LI-COR readout and Instrument 2 approximately 2 lux below the reading in a largely daylit office with the artificial lights turned off. This reveals that in a more natural, real world setting (where light is coming from the side), values provided by the Extech instruments may slightly underestimate the actual value, despite being greater in the lamp experiments where most of the interior light was coming from a beam directly in-line with the axis of the sensor.

II.I.2 Indoor and Outdoor Lighting Experiments

A second phase of instrument experimentation focused on evaluating lighting conditions in a variety of settings with the goal of further distinguishing instrument 1 and 2's performance at the low range and assessing their accuracy at higher lighting levels as well. Moreover, real world measurements both inside and outside (given clear sky conditions experienced on that date) might provide a better indication of performance in conditions more typical of those inside and outside of churches. Chantal Arsenault of the NRCC again generously provided the direction and materials for the experiment, attaching instrument 1 and 2 sensors to a small platform with the LI-COR sensor directly between the two and constructing a box-style platform to allow the instantaneous viewing of each readout device. During this phase of experimentation, many of the measurements were made with an observer holding the platform and reading off values and another observer recording the values. This led to slight shaking and an inability to read all numbers at the same, which resulted in unavoidable experimental errors.

However, the results obtained remained fairly consistent and are presented in Tables 3.1 and 3.2. As seen in Table 3.1, in the low range under higher lighting conditions (particularly above 100 lux), the Extech meters were both as much as 20 to 30 lux below the LI-COR instrument values, and this may be due in part to the design flaw associated with the elevated ring around the Extech instruments mentioned earlier. Error values were calculated for the low range measurements of both instruments (with the LI-COR instrument values again held as the accepted

values) for only measurements where there was a substantial proportion of side-lighting (as is the case in all interior measurements taken in churches). The results reveal that Instrument 1 had error percentages varying from -7% to -21% without any apparent trend in error variation with increasing or decreasing lux values (although errors for values under 100 lux appear to be smaller for Instrument 1). On the other hand, Instrument 2 showed a more consistent average error of -16% (with an error interquartile range of only 1.69%). The errors were notably lower (-0.55% for Instrument 1 and -3.86% for Instrument 2), however, for an instrument reading (not shown) facing a florescent lamp where the vast majority of light was coming from above the sensor, and this observation is relatively consistent with the greater accuracy of the instruments in the lamp experiment where the majority of the illuminance is coming from above the sensor.

Table 3.1: Low Range Experiment (only readings where light from the side and from above the sensor are important)

Low Range Sensitivity Experiment

LI-COR 250A	Instrument 1	Instrument 2	Instrument 1 % Error	Instrument 2 % Error
9.7	9	8	-7.22	-17.53
133.3	105	110	-21.23	-17.48
147.6	121	122	-18.02	-17.34
283.2	252	252	-11.02	-11.02
331.3	290	279	-12.47	-15.79
1411.6	1191	1173	-15.63	-16.90

At the middle and high ranges, the numerical drift between the LI-COR and both Extech Instruments was notably higher (see Table 3.2), indicating that with greater lighting levels the difference between the absolute and accepted values associated with the design flaw or other source of error become more egregious (but the percent error remains the same). This large difference between the observed value and the actual value has the potential to influence our daylight factor calculations. However, Instrument 1's mid and high range values continued to be quite close to the LI-COR values and appeared to always underestimate the lighting for both horizontal and vertical measurements taken indoors and outdoors, allowing for a general correction to be applied to the data for all ranges using a correlation equation to estimate the likely actual value. In addition, it is also notable that the average error between the two instruments is relatively lower for the high range, where sunshine is an important part of the measurement, and greater for some mid range measurements where diffused lighting intensity from different directions varied. Sun inclination above the device, as well as its intensity, is expected to be behind the some of the errors at the high range (likely due to cosine correction). In an assessment of Instrument 2's

performance at the high range, the device showed no clear consistency with the LI-COR readings, being completely off in an actual numerical sense. However, further analysis (presented in the next section) shows a nearly perfect linear correlation between Instrument 2 high range values and the LI-COR readings, suggesting that the Instrument 2's high range values were substantially inaccurate due to problems associated with the readout or the resistor. Further, the values obtained during experimentation are clearly not random (as they strongly co-vary with respect to the actual value), and thus we can correct the Instrument 2 values toward the accurate value.

Table 3.2: Middle and High Range Values taken Outside in Various Orientations on 21 September, 2007

Middle and High Range Sensitivity Experiment

LI-COR	Instrument 1 Mid Range	Instrument 1 High Range	Instrument 2 High Range	Instrument 1 % Error Mid Range	Instrument 1 % Error High Range	Instrument 2 % Error High Range
2990	2350			-21.40		
3094	2740		16600	-11.44		436.52
3178	2840		17300	-10.64		444.37
4811	4480		27100	-6.88		463.29
5023	4750		28400	-5.43		465.40
7430	6930		43100	-6.73		480.08
9231	7080		57700	-23.30		525.07
11594		10800	71700		-6.85	518.42
12266		11200	71700		-8.69	484.54
24630		22600	149000		-8.24	504.95
70800		64500			-8.90	
72470		71700			-1.06	
75690		66800			-11.75	

II.1.3 Resulting Data Modification

For very dark conditions, LI-COR and instruments 1 and 2 appeared to provide similar values (at the lower ranges). Although Instrument 1's values are consistently greater than those of Instrument 2 during a variety of experiments, they remained reasonably close to each other and well within the error range of the two instruments. Therefore, no corrections between the two instruments and the LI-COR meter were applied in further analyses (although Instrument 1 and Instrument 2 were readjusted with respect to each other below). In addition, the higher end (over 200 lux) of both instrument's low ranges underestimated light levels by as much as 20-40 lux. However, since most measurements within churches were substantially under 200 lux (and many thirteenth century interiors had daylighting components below 20 lux in diffuse lighting conditions), no corrections at the low ranges of either instruments with respect to the LI-COR

readings were deemed necessary. Further manipulation of the instrument data with respect to each other, however, is done in the instrument sensitivities section below.

Instrument 2's high range, on the other hand, required some sort of conversion method to allow for further data analysis. The percent error in Table 3.2 shows that error from the accepted values remained relatively consistent and thus could be reasonably eliminated by adjusting up the accepted values. The LI-COR and Instrument 2 high range values were plotted on a simple scattergraph (Figure 3.1), and given the clear linear relationship between the two values a least squares regression was performed to provide an equation relating the two values. The linear coefficient of correlation between them was $r^2 = 0.994$, which was deemed highly statistically significant (according to the Pearson Coefficient) despite the modest degree of freedom of the dataset.

Given the high statistical significance of this strong correlation, the least squares linear equation was used to 'convert' between Instrument 2 high range values and LI-COR values, and it was applied to each of the Instrument 2 high range data points to create an estimation of the actual value of exterior illuminance. However, converting directly between the two instruments eliminates the underestimation that would otherwise exist (due to the design flaw of the instrument or some other mechanism). The same error may still be present at the same magnitude in interior measurements as well (as also suggested by the one measurement comparison between the LI-COR meter and instruments 1 and 2 in an NRCC office with the lights off). Because we do not have at this time enough comparison data to upward adjust all of the low range interior values to the LI-COR values, we decided for the purposes of daylight factor analysis to instead downward adjust the actual value estimates of Instrument 2's high range measurements by using a least squares line of best fit as a conversion equation between Instrument 1's middle and high range and Instrument 2's corresponding high range. This method would give values according to the way an Extech instrument sees it, and it perhaps also serves as a more accurate way to upward adjust the values, as many more data points comparing the high range of Instrument 2 and the middle and high range of Instrument 1 were collected on our own time to ensure greater statistical soundness.

This type of conversion allows the respective underestimations due to the design flaw to essentially cancel out when indoor and outdoor values are proportionately treated. However, when the interior instrument analysis involved placing the Extech sensor close to a window and nearly vertical to it (such as in glazing transmission measurement), the instruments are expected to

behave similar to lamp conditions (where the greatest illumination is directly in front of the instrument's sensor and the otherwise observed underestimation error is minimal). In these cases, the accurate (LI-COR) conversion of Instrument 2 high range is used. The same equation used to predict LI-COR values and Instrument 2 values was used to convert between predicted Instrument 2 output given Instrument 1 values.

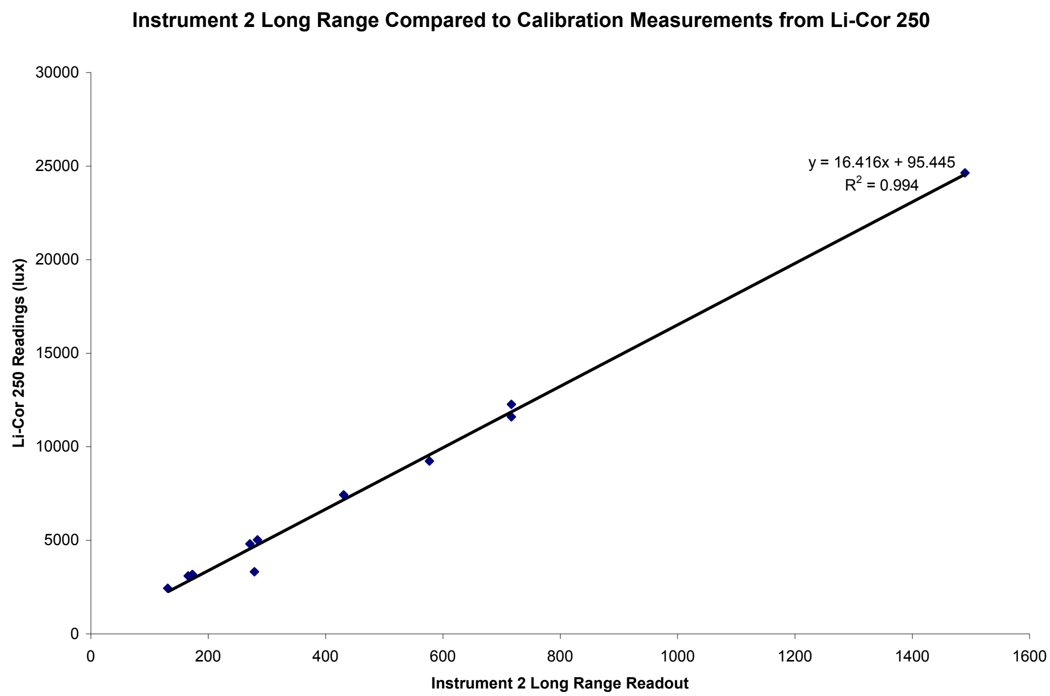


Figure 3.1: The Scattergraph correlation between the Instrument 2 High Range readout and LI-250A measurements

II.2 Instrument Sensitivity Tests

Extech provided us with two replacement instruments to account for the aforementioned defective qualities of instruments 1 and 2; they were randomly labeled Instrument 3 and Instrument 4. In order to determine the sensitivity of these devices compared to the two verified instruments 1 and 2, a series of sensitivity tests were performed, both before and after the second (winter 2007 - 2008) research trip to Europe. The four instruments' sensors were strapped to the same square platform with a black background, and a series of measurements were conducted at all ranges. In order to ensure that the zero calibration and orientation of the sensors would not substantially affect the mean measurement variation, the sensor positions were occasionally switched and recalibrated at random. Because the lower part of the low range is the most commonly used section in Medieval churches, we devoted a particularly large number of

observations to documenting the range of values possible among the instruments associated with each particular measurement. Most of the experiments (over 500 observations) were conducted in an office setting, and although the instruments were directed toward a variety of surfaces with different reflective properties and colours, most of these observations were taken in the direction of a white ceiling.

We also performed separate experiments with different qualities of light: daylighting only, tungsten (incandescent only), tungsten and daylighting, and two kinds of incandescent lighting alone and with daylighting. Documenting these different lighting regimes under the same colour mode (L), the configuration used in Europe for all operations, ensured that the experiments covered a variety of different spectral patterns to reflect any variations in spectral sensitivity between the instruments. In addition, most of these measurements were taken of indirect, reflected light, i.e., the meters were often directed away from a light source and toward an illuminated surface to minimize the reading errors associated with the sensors' positions relative to each other. These office lighting experiments were then compared to real world data, especially between instruments 1, 2, and 4. Comprehensive results and statistical analyses of these instrument sensitivities are summarized here (all of the regression equations discussed here are highly statistically significant according to the Pearson Coefficient method).

In order to reduce the errors associated with each meter, Instrument 1 was used during the interior analyses of most cathedrals, while Instrument 2 was used only during clear sky conditions (spring 2007 experiments in Bourges and Chartres) where Instrument 1 was needed on the outside. Then, during the majority of the winter (2007-2008) and summer (2008) experiments, Instrument 4 was used in all interior measurements (with the exceptions of Toledo, Segovia, and St-Ouen, Rouen). Thus, for most interior measurements Instrument 1 and Instrument 4 were used exclusively. In the office experiments, Instrument 1 and Instrument 4 demonstrated essentially the same output, with a statistically significant least-squares correlation between the two yielding an equation with output suggesting that the predictor (Instrument 1) and predictand (Instrument 4) equal each other for 0-12 lux, with Instrument 4 falling behind by 1 lux thereafter for the rest of the experiment range (20 lux). Thus, Instrument 1 and Instrument 4 appear to possess roughly the same sensitivity in the office settings experiments, and we shall define in further references that Instrument 1 and Instrument 4 are the standards for comparison. Another evaluation between these two experiments was afforded by the real world setting of Strasbourg Cathedral's interior lighting

at night. The two lighting regimes were not exactly equivalent in the nave (although close), but the statistical test was limited only to side aisle measurements (where tapestries blocked most of the nave lighting). It revealed the same trend—the least squares linear regression equation predicted that Instrument 1 and Instrument 4 provide the same values simultaneously for 0-12 lux and Instrument 4 exceeds Instrument 1 by 1 lux from 12-20 lux. Given these results, we conclude that Instrument 1 and Instrument 4 can be used interchangeably in the low range of values. Thus, we used, when necessary, nighttime measurements taken by Instrument 4 subtracted from daytime measurements taken by Instrument 1.

Instrument 3 was used most of the time on the outside, where it showed similar results with the other instruments. On the inside it was used in only two cases—one (St-Ouen) at the higher end of the low range, where it yielded very similar results to instruments 1 and 4, and another (Toledo) at the low end of the low range. In the same procedure described above performed between Instrument 3 and Instrument 4, the regression equation predicted that Instrument 3 falls behind Instrument 2 by about 1 lux for all values 0-20 lux. During the office experiments 2 lux was the highest value obtained on Instrument 4 when Instrument 3 held a zero. Thus, all zeros provided by Instrument 3 were assumed to be equivalent or less than 1 lux (and not more than 2 lux) on Instrument 4. This distinction becomes important in our claims concerning the lighting aesthetic in Toledo cathedral's crossing, transepts, and ambulatory.

Instrument 2 is the focus of more attention because it appears to vastly underestimate the bottom of the low range in illuminance in some cases (but not in all situations), and there is also plenty of comparison data between Instrument 2 and instruments 4 and 1 in the cathedral setting. Instrument 2 in the office experiments consistently held a value of zero as instruments 1 and 4 would approach 5 lux, and then when instruments 1 and 4 would reach a value of 6-7 lux Instrument 2 would arrive at 1 lux. The resulting regression between instruments 2 and 4 predicts that Instrument 4 is 5 lux higher than Instrument 2 for the first 6 lux and 6 lux greater than Instrument 2 thereafter (up to 20 lux). Using only the data from Bourges Cathedral (exclusively daylighting measurements) indicates that Instrument 4 is only about 4 lux greater than Instrument 2 for most measurements up to 20 lux. The differences between the regimes may be due to the greater direct lighting received in the Bourges ambulatory (due to the low elevation of the windows), in which Instrument 2 tends to perform better (see above). Because the two regimes

(office and Bourges) otherwise demonstrated close similarities, they were combined for only the 1-21 lux range of Inst. 2 and the resulting equation (I.1), was applied to all

$$(\text{Inst. 4 value}) = 0.9817 \cdot (\text{Inst. 2 value}) + 5.1913 \qquad \text{(I.1)}$$

Instrument 2 values in the Chartres spring partly cloudy analysis (after the Instrument 2 subtraction of the nighttime artificial lighting component) to obtain a more representative estimate of interior illuminance associated with Instrument 2 measurements. This procedure is justified given the high (6-10 lux) values obtained by Instrument 1 in the north aisle slightly earlier in the afternoon, and by the fact that the illuminance on the north side of the cathedral was becoming brighter on due to the changing orientation of the sun (which does not justify the 1-3 lux values obtained in this region using Instrument 2 later in the late afternoon).

However, an analysis of Instrument 2's performance in typical cathedral artificial lighting conditions reveals that it is only slightly less sensitive than instruments 1 and 4, lagging behind by only 1-2 lux at the bottom end of the low range. This is true when comparing instruments 2 and 4 in Chartres and Strasbourg and instruments 1 and 2 in Strasbourg. Thus, it is important to distinguish between Instrument 2's performance in the Office/Bourges regime to those of spot artificial lights (to which instruments 1, 2, and 4 are nearly equivalent in sensitivity at the bottom end of the low range). However, Figure 3.2 also reveals that the two regimes merge for increasingly larger quantities of artificial lighting (over 10 lux).

Other experiments were also performed to demonstrate the instrument performances relative to each other in colder conditions at 5°C (kept at that temperature for two hours before use), typical of cathedral interior temperatures during the winter observations. No change in sensitivity was observed between the instruments, as we expected from the instrument specifications. In addition, for another experiment the sensors associated with each individual instrument were switched and a variety of data were collected, which proved that the readout meters rather than the sensors themselves are the source of almost all of the observed sensitivity variation between the instruments. With this in mind, the ring from one of the sensors was severed to test if the values obtained by a ringless Instrument 1 were closer to that expected by the Li-Cor meter (using the Instrument 2 equation), and this was confirmed for values between 2000-10000 lux (thus suggesting that the ring may be the source of much of the error between them). However, the failure to reproduce expected Li-Cor readings at the lower ranges (100 - 1000 lux) and higher

ranges (10000+ lux) demonstrates that some other sources of error may be responsible for the Extech 407026 underestimation beyond the mid range.

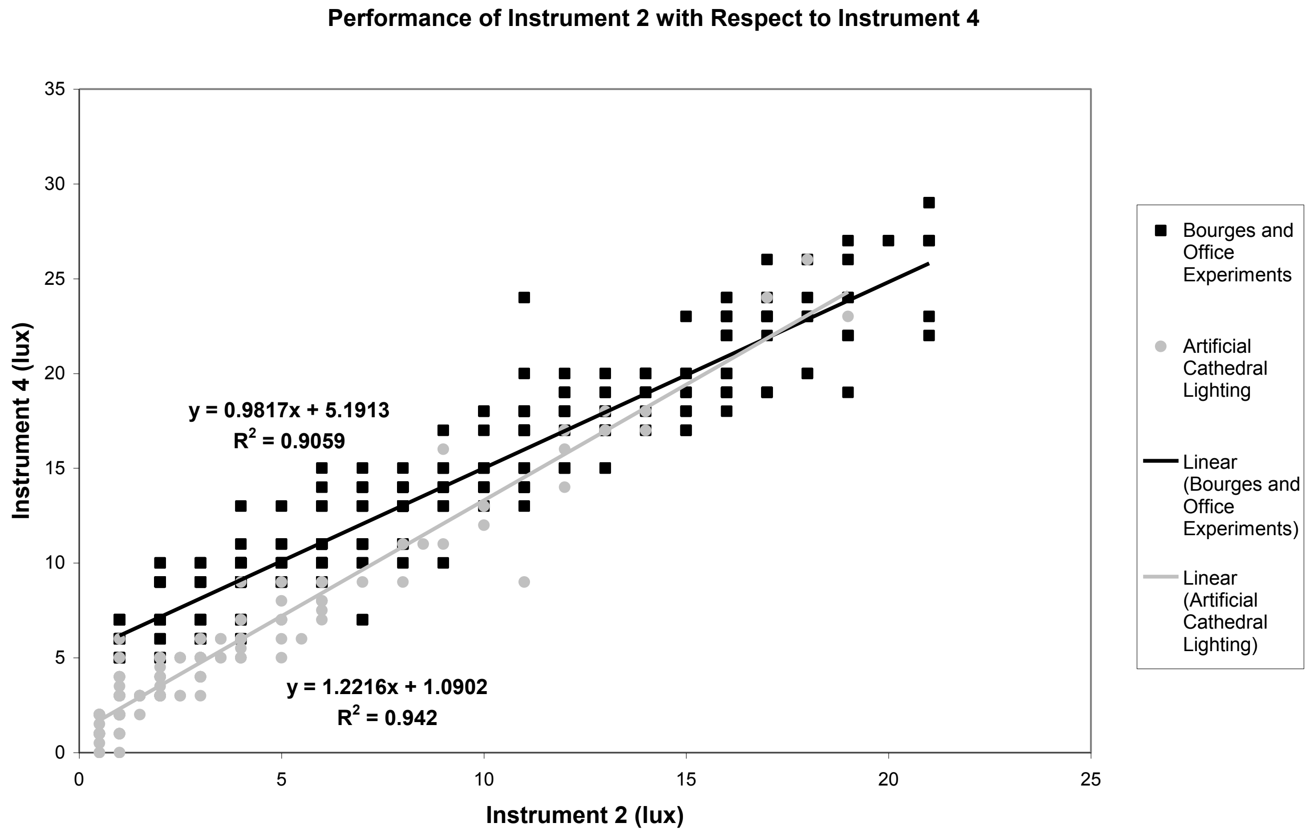


Figure 3.2: Sensitivities of Inst. 2 and Inst. 4 during office and Bourges experiments (black squares) vs. artificial cathedral lighting situations (grey circles). Some of the data points from the artificial cathedral lighting dataset actually extend from Inst. 1 vs. Inst. 2 in Strasbourg, with Inst. 1 and Inst. 4 considered approximately equivalent.

Appendix III: Representing Daylight Factors in the Ambulatory of Bourges Cathedral

During data collection in Bourges cathedral, overcast measurements were taken twice in the ambulatory to ensure consistency. One round of measurements was taken during a period (944-947 GMT) of brightening toward the sun (but nearly constant exterior horizontal illuminance between measurements) and once (1417-1427 GMT) under a CIE standard overcast sky with increasing cloud thickness (and constantly decreasing exterior horizontal illuminance). For a few places, such as locations 2 and 7 in Figure 4.5, three measurements were available, including a round taken under a patchy (darker patches in some clouds) overcast sky (907-911 GMT). For the standard overcast sky measurements, taken 16 minutes apart, a variety of methods were used to estimate the decay of exterior horizontal illumination (linear, polynomial and exponential regressions between four measurements taken over a 30 minute period), and they were averaged to produce an estimate of the horizontal illuminance values during the 16 minute period. These approximate daylight factors were then compared to the CIE standard overcast sky 4 horizontal illuminance proportions to ensure some degree of consistency, taking into account that the consistently overcast sky standards behave relatively similarly with respect to each other (Bartzokas et al, 2003, Fig. 1). Under the patchy overcast sky, the measurements taken at locations 1-12, provided very low daylight factor estimates (0.01 to 0.03 % HDFs) compared to the estimated daylight factors in the standard overcast sky in all cases except Location 3. The sky associated with a brightening toward the sun, however, provided very precise measurements compared to the standard overcast sky for locations 2, 7, 13, 14, and 16. Therefore, the south ambulatory measurements under the standard overcast sky are probably relatively accurate. Because this mode is preferable for daylight factor calculations, the non-averaged values for HDFs determined between 1417 and 1423 GMT (locations 1 – 16) were presented in Figure 4.4a of the thesis text (see below). However, the north ambulatory daylight factors diverge significantly for points 17 to 24; in particular, locations 17, 19, 21, 22, and 24 these factors average 0.039%, contrary to the standard overcast sky which averages 0.080% for these points.

The clear south triforium windows that directly illuminate the north ambulatory may contribute somewhat to the higher daylight factors in this region; however, if this were truly the case then the sky representing brightening toward the sun example should have produced the higher daylight factors. Because the CIE Sky Standard 4 produced the most precise results when

compared to the CIE Sky Standard 1, the CIE Sky Standard 4 measurements are expected to produce the most believable daylight factor values for the north ambulatory. Therefore, errors in estimating the exterior horizontal illuminance between 1423 and 1425 GMT might have provided a significant overestimation of daylight factors in the north ambulatory. However, in order to reproduce the proportions calculated for the 944-947 GMT measurements, exterior measurements between 1423 and 1425 would need to approach 8000 lux, which we consider unreasonable considering the start (5410 lux at 1414 GMT) and end (3330 lux at 1430 GMT) values. In addition, this exterior horizontal illuminance seems even more unlikely given the daylight factor estimation of 0.14% to 0.25% under direct lighting from a Fourteenth century window at 1426 GMT when provided with an approximate exterior horizontal illuminance of 3556 lux. This daylight factor is consistent with other examples of measurements in the presence of similar glass taken at different times. Therefore, instrumentation (rounding) errors may have provided an overestimation of the interior illuminance during the 1423-1424 GMT observation and an underestimation during the 944-947 GMT observations.

Therefore, in the case of the north ambulatory an average of the two rounds of measurements available (standard overcast and brightening toward the sun) is deemed more appropriate than simply presenting just one round of measurements, which provides an average HDF in the aforementioned ambulatory locations of 0.059% and 0.107% for the two north chapels (locations 18 and 23) together. Then, a simple test on the sensitivity of this average daylight factor to errors in estimating the exterior horizontal illuminance trend is evaluated. The measurement at location 16 is the last highly-precise measurement of the 1410-1430 GMT observations (when compared to the 944-947 GMT measurements). Assuming that the reason for the increased divergence is in part an underestimation of the exterior horizontal illuminance, we first fixed the exterior horizontal illuminance between 1423 and 1425 GMT at the 1423 GMT value, estimated by using location 16's precise average daylight factor. This yields a horizontal illuminance of 4168 lux, which is kept unchanged for the north ambulatory measurements between locations 17 and 24. This yields an average daylight factor for locations 17, 19, 21, 22, and 24 of 0.055%, and for the two chapels, 0.101%. We can also reasonably conclude that, if the exterior illuminance between these two increased over the interim between 1423-1425 GMT, the exterior horizontal illuminance would not have likely been above 5000 lux if 4168 lux is the likely maximum value at 1423 GMT and 3556 lux is a reasonable value at 1426 GMT (with persistent, thick overcast conditions during

all observations). Assuming a fixed exterior horizontal illuminance of 5000 lux between 1425-1425 GMT, we obtain an average daylight factor of 0.049% for the ambulatory bays and 0.091% for the chapels combined. Therefore, it is reasonable to presume that for most points, the average daylight factors in the north ambulatory (0.059%) may be in fact closer to the range of 0.049%-0.055% if the exterior horizontal illuminance was underestimated, and for the chapels the corresponding daylight factor range is 0.091%-0.101%.These are not substantial diversions from the known average HDFs at 0.059%, and thus the results for the average daylight factors in the north ambulatory are considered pertinent and are represented in Figure 4.4b.

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