Syncing with the Sky:
Daylight-Driven Circadian Lighting Design

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Abstract

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The use of daylight in the built environment is preferred to artificial sources as it provides visual comfort and satisfaction along with significant energy savings. Daylight is also the primary source for stimulus that establish a healthy day/night cycle, or circadian rhythm. With the discovery of photosensors within the eye that are specifically linked to the portion of the brain responsible for maintaining a healthy circadian rhythm, a new field of lighting design has come in to being focused on controlling the spectrum of light that they are sensitive to.

Currently, work in this field of lighting design, called circadian lighting design, is concentrated on artificial sources circadian stimulus. This is largely due to

the advent of the widespread use LED technology, which has proven that it can be a significant source of circadian light. The use of daylight to provide circadian stimulus has been a given in this field of design, however, there has not been very much research into how the built environment affects our ability to effectively receive this stimulus from daylight.

In this thesis, the groundwork will be established to start to create a set of guidelines to help architects and designer maximize the potential for daylight to provide circadian stimulus at the earliest stages of a project. This is accomplished through a series of case studies and lighting simulations that explore and test various architectural parameters that affect daylight-driven circadian lighting.

Acknowledgments

I would first like to thank professor Mehlika Inanici for introducing me to the topic of circadian lighting, and sharing with me her vast knowledge in this field. Her guidance in this process has been invaluable in broadening my understanding of light in the built environment and its affects on human health and wellbeing. I am very fortunate to have met her and received her mentorship. I would also like to thank her for her lessons in the use of grasshopper, without which I would have not been to produce half of the work in this thesis.

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1. Introduction: Daylight-Driven Circadian Lighting

Circadian lighting is a new field of design that has come into existence in the last decade in response to recent developments in photobiology that have found a direct quantifiable link between exposure to light and circadian rhythms. This link has identified how exposure to a particular spectral range of light towards the blue end of the spectrum causes a shift in the circadian rhythm of humans and other animals that can increase alertness and reduce sleepiness. This shift, under natural light, entrains the individual's circadian rhythm to the day-night cycle in their environment and corrects for any offset in their internal sleep-wake cycle to cause them to be alert during day-lit hours and sleepy at night. The current practice of circadian lighting design is focused on the effect of artificial light on the circadian pacemaker as it can have both a desirable and an adverse effect on human well-being. This practice however has not expanded upon the effective use of daylight for circadian stimulus.

While it is important to understand and quantify the effect of artificial light sources on circadian entrainment in order to be provide supplemental stimulus when needed and prevent undesirable stimulus that can have an adverse effect on human and animal well-being, it is also essential to understand the effect of the built environment on the natural light that humans have evolved to be entrained to. This distinction is similar to the distinction between electric lighting design and daylighting in that electric lighting can be used for

supplemental purposes to provide light when necessary during the day, but ideally the effective use of daylight is maximized in order to reduce energy usage and provide natural light for human well-being. Unfortunately, it is common to assume that effective daylighting design will be sufficient to provide circadian stimulus. This assumption is false, as current lighting design standards focus on providing sufficient illuminance on a worksurface or floor for various tasks and maximizing visual comfort through glare control, while circadian stimulus is reliant upon the spectral quality and intensity of light entering the eye.

The difference in these metrics is key to understanding the effectiveness of daylight in providing circadian stimulus in the built environment. The typical method for measuring worksurface illuminance uses an illuminance sensor placed horizontally 30 inches above the floor (typical worksurface height). This sensor measures the quantity of visible light striking a point on the worksurface from 180° hemisphere pointing vertically up off the worksurface as depicted in figure 1.1. Measuring for circadian stimulus uses a circadian illuminance sensor placed vertically 48 inches above the floor (typical eye height of a sitting person), which measures the quantity of circadian light (light within the spectral range that effects circadian rhythms) striking the retina from a 180° hemisphere pointing horizontally in the intended direction of view of the occupant as depicted in figure 1.2. The key differences in these metrics is the height above the floor surface, the spectral range of light being measured,

and the orientation of the sensor. Due to the vertical orientation of the sensor, measurements of circadian light are very directionally dependent, causing large variances within the range of measured values within a room as compared to typical lighting measurements made by a sensor placed horizontally on a worksurface. In addition to this, photopic and circadian illuminances have different units and target values. Although these will be discussed in detail in Chapter 3, it is suffice to say that photopic values are measured in lux, with target values between 300-3000lx, and circadian illuminances are measured in equivalent melanopic lux (EML), with a target value of 240 EML.

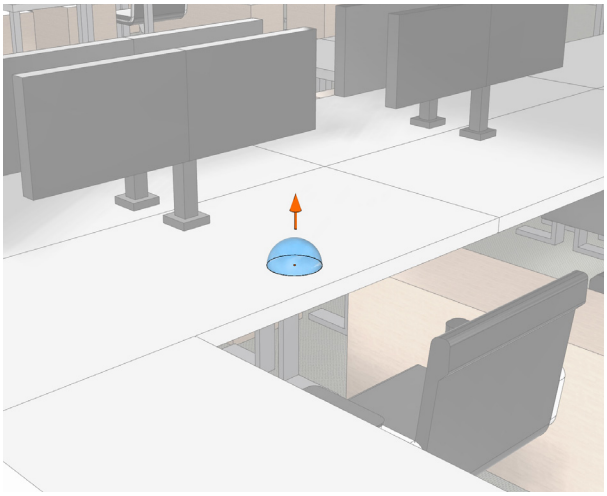


Figure 1.1. Horizontal light sensor typical in photopic lighting standards pointing vertically up off a work surface 30" above floor finish.

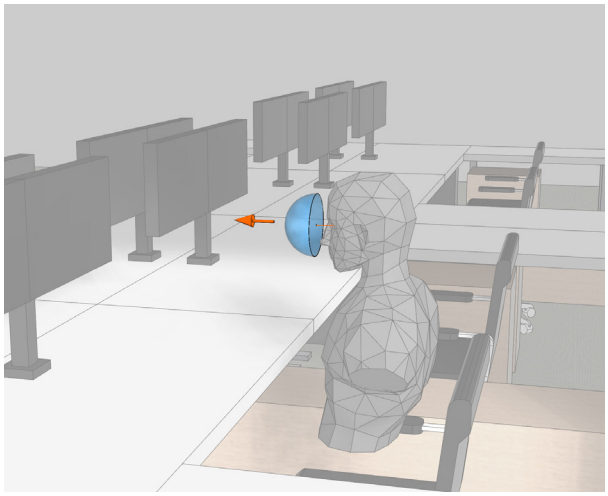


Figure 1.2. Circadian light sensor placed on a vertical plane 48" above floor finish pointing horizontally in the intended direction of view of the occupant.

While some measurements for glare control also use a vertical sensor similar to the sensor used for measuring circadian stimulus, these measurements are mainly focused on identifying luminance values above acceptable levels for visual comfort. Due to the non-visual nature of the photoreceptors responsible

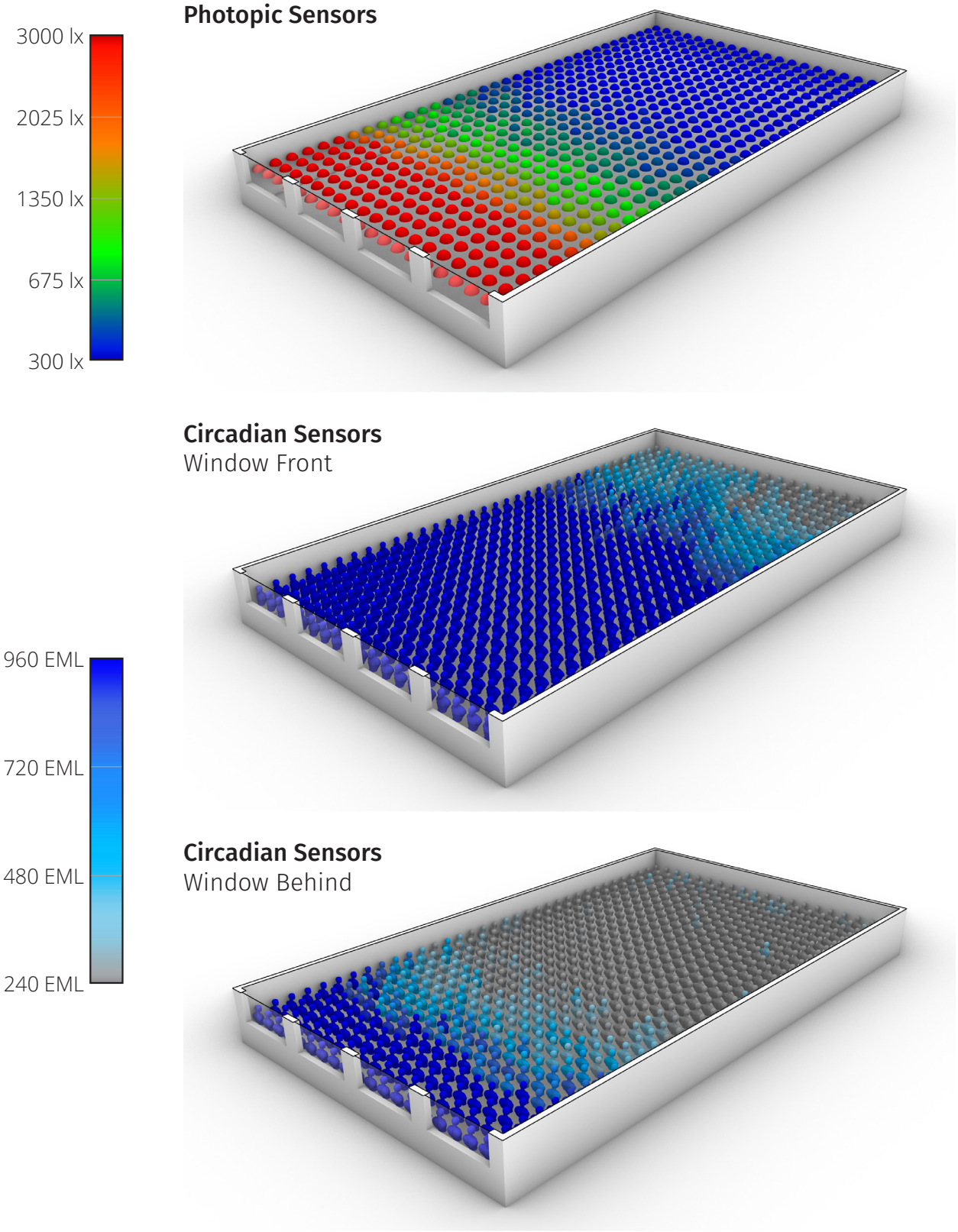


Figure 1.3. Example of a simulation illustrating horizontal photopic sensors (hemispheres) vs vertical circadian sensors (human figures) facing towards the window and facing away from the window.

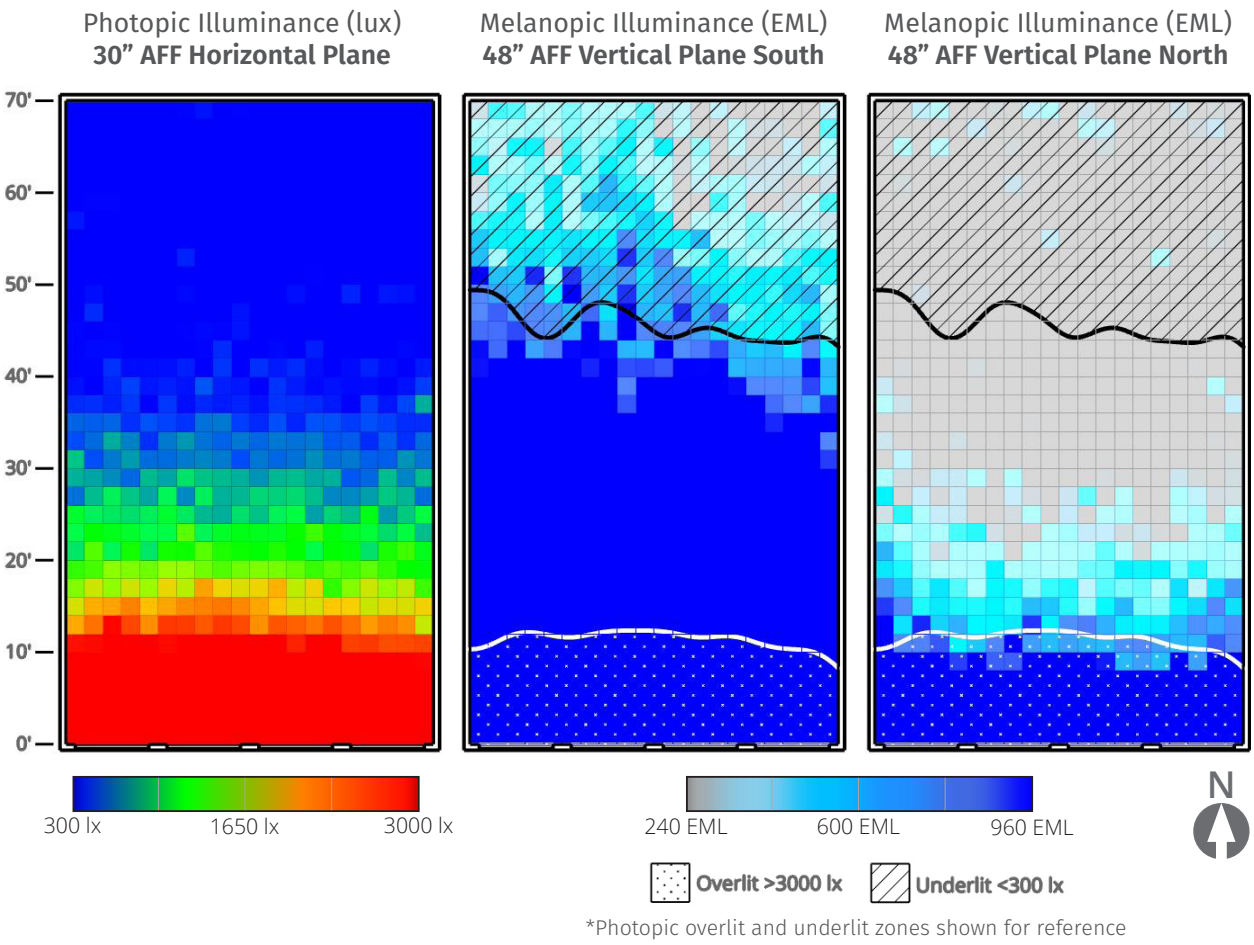


Figure 1.4. Plan view visualizations of the simulation from figure 1.3

for circadian stimulus and the slow response time of these photoreceptors, glare is not an issue for circadian stimulus. Additionally, the goal for circadian stimulus during the day is intended to maximize exposure at or above target values over a period of time sufficient to entrain the circadian pacemaker. This goal can be conflicting in nature to the goals for glare control, which are intended to minimize exposure to luminance values that can create visual discomfort. However, as visual discomfort can cause an individual to deploy shading devices or move away from the source of discomfort, and in turn reduce the quantity of light entering the eye and effectively reduce circadian

stimulus, glare control still takes precedent over metrics for maximizing circadian stimulus during the day.

The objective of this thesis is to begin to generate guidelines that may help designer to more effectively utilize daylight to provide circadian stimulus to the occupants within an office environment. In order to achieve this goal, it is necessary to better understand the current effectiveness of daylight in providing circadian stimulus within various office spaces today. It is also necessary to establish a methodology for simulating and analyzing daylight-driven circadian illuminance within a given space. These goals are achieved through series of case studies of various office spaces, and the simulation and analysis of various architectural parameters within a simplified office model in order to determine their effect upon the circadian illuminance of a space.

2. Background: Photobiology and Circadian Rhythms

This chapter is a brief introduction into the current research from photobiology on circadian rhythms. While much of the research on this subject is still in its early stages and the comprehensive impact on human health is not completely understood, the current findings do reveal a significant connection between light exposure and the human endocrine systems. This section explains this connection.

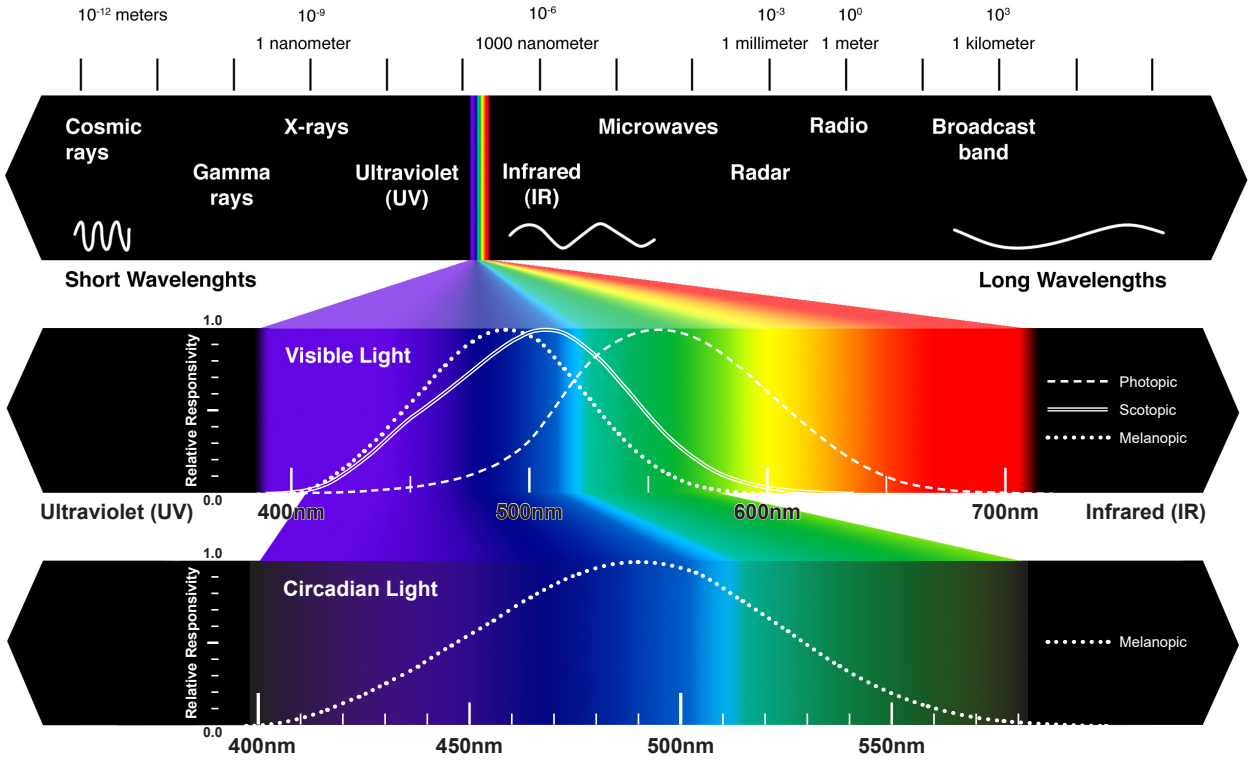


Figure 2.1. Visible light spectrum vs circadian light spectrum as defined by photopic sensitivity range and melanopic sensitivity range respectively.[1]

2.1. Visible Light versus Circadian Light

The visible portion of the electromagnetic spectrum, or visible light, occurs in wavelengths between 380nm and 780nm. The main body of research

in photobiology has been in understanding how visual systems translates these electromagnetic waves into neural responses that allows for vision. This research has revealed that humans and many other animals have both visual and non-visual systems for responding to light. The non-visual system for humans responds to a smaller range of wavelengths, approximately 390nm to 600nm, which will be defined here as circadian light.[2] Both the visual and non-visual systems are linked to sensory cells within the retina of the eye and defined by their corresponding spectral sensitivity ranges.

2.2. Anatomy of the Eye

The eye is the organ that allows for sight in humans made up of many components including a cornea, iris, pupil, lens, vitreous, retina, macula, fovea, and optic nerve.[3] These components work together to focus and process light into a neural stimulus which is transmitted to the brain to be processed into vision and other internal biological responses.

Cornea – The transparent outer layer over the Iris that functions like a camera lens to focuses light into the pupil.

Iris and Pupil – The iris is the colored portion of the eye which expands or constricts the size of the opening in the center of the iris, or the pupil, to control the quantity of light entering the eye, similar to the aperture in a camera.

Lens – The transparent body behind the pupil which focuses the light entering

the eye onto the retina to increase visual acuity.

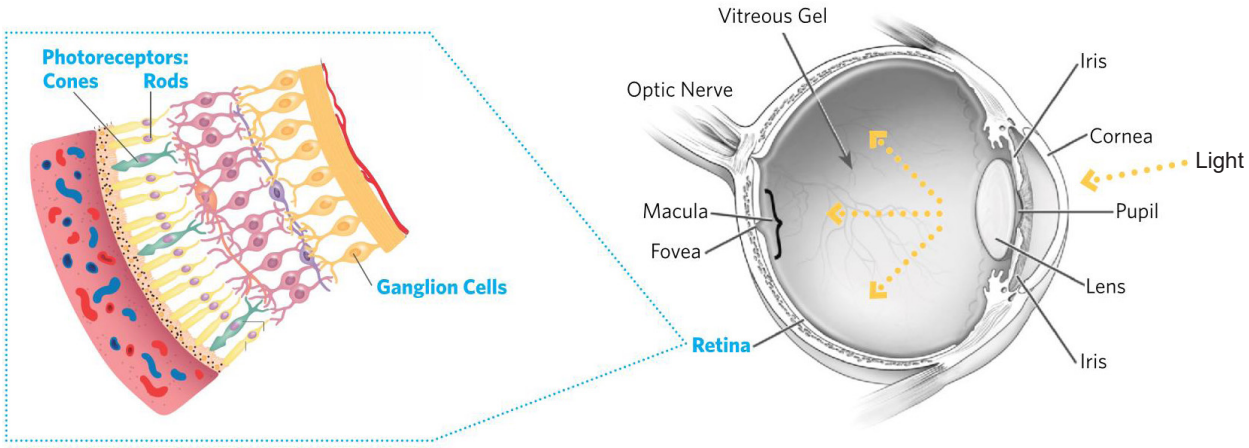


Figure 2.2. Anatomy of the human eye.[4]

Vitreous Gel – The transparent jelly like fluid within the eye that fills the central cavity of the eye and allows for light to reach the retina.

Retina – The surface at the back of the eye which contains blood vessels, and a variety of photoreceptor cells along a layer of nerves used for converting light into neural stimulus.

Macula and Fovea – The macula is the central area of the retina which contains a higher density of photoreceptors required to process high visual acuity within an approximately 60° central field of view. The central depression within the macula, called the fovea, contains the highest density of photo receptors within the eye for processing the sharpest vision within an approximately 2° central field of view.[3]

Optic nerve – The bundle of more than 1 million nerve fibers connected to the

back of the eye which transmits the neural stimuli from the retina to the visual cortex of the brain.

2.3. Visual System

The retina is the key feature of the eye for converting light into neural stimulus. It does this through the use of photo receptor cells, which use of photopigments that are unique groups of proteins, also called opsins, that respond to specific ranges of electromagnetic wavelengths.[5] As a photon within the wavelength sensitivity range of the photopigment enters the photoreceptor cell, it causes a chemical reaction within the protein group that induces it to change in shape, triggering a reaction within the cell that creates a neural output.[5] Within the human eye, there are four types of photoreceptor cells that contribute to the visual system, one rod cell, and three types of cone cells.

The rod cells are the most common photoreceptor cell with more than 120 million occurring throughout the retina.[5] These cells use a photopigment called rhodopsin which responds to the blue-green portion of the visible spectrum with a peak sensitivity at approximately 507nm.[5] Rhodopsin is extremely sensitive to light. This allows the rod cells within the retina to contribute primarily to vision in low-light condition with light levels below 0.001 cd/m2, or scotopic vision.[6] However, rhodopsin can become oversaturated and bleach when exposed to light levels greater than approximately 3 cd/m2. This causes rods to be ineffective in contributing to vision in brightly lit environments.

Once bleached, rhodopsin in humans requires approximately 30 minutes to regenerate and become sensitive to light once again.[5]

There are three types of cone cells within the human retina each containing a variant of the photopigment photopsin. There are approximately 6 million of these photoreceptor cells located primarily within the macula, with the highest density occurring within the fovea.[3] The three types of photopsin photopigments each respond to a different range of the electromagnetic spectrum.

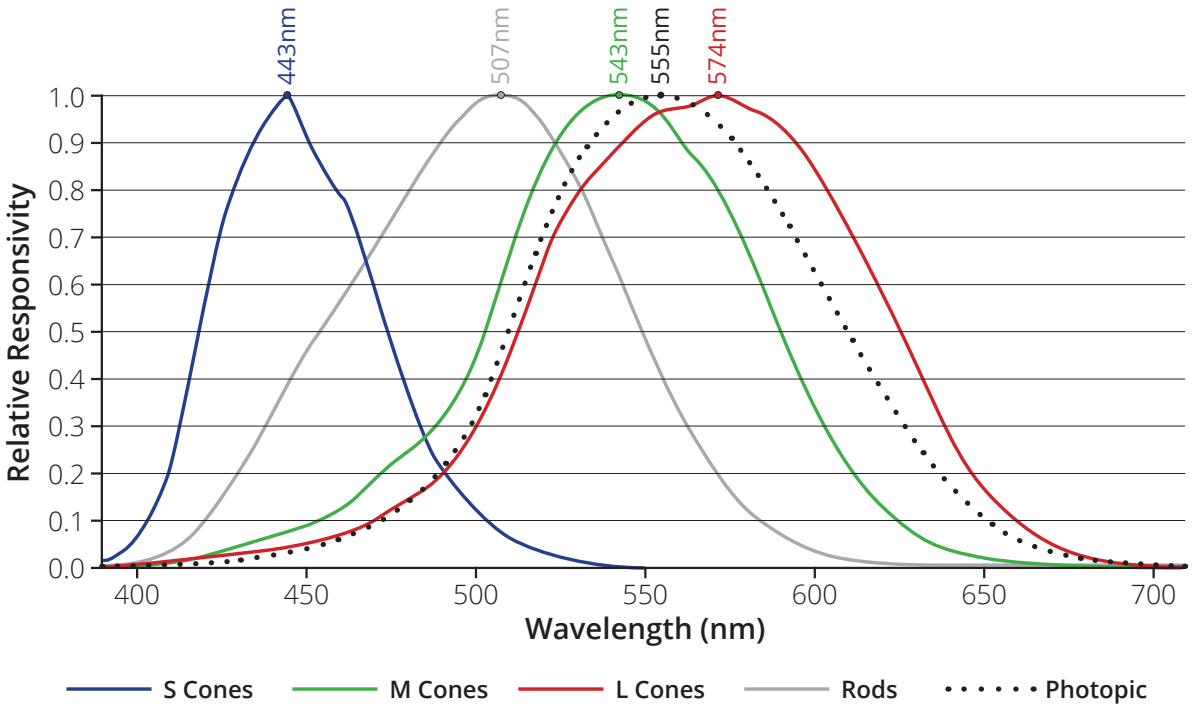


Figure 2.3. Relative responsivity of S, M, L cones, rods, and combined photopic vision.

The long wavelength sensitive opsin, or L-opsin is the photopsin sensitive to the green-yellow-red region of the visible spectrum between 500-700nm with

a peak sensitivity at approximately 574nm.[5] These photopigments are found in the red cone cells within the retina. The medium wavelength sensitive opsin, or M-opsin is the photopsin sensitive to the green region of the visible spectrum between 450-630nm with a peak sensitivity at approximately 534nm.[5] These photopigments are found in the green cone cells within the retina. These red and green cone cells can be found primarily in the fovea and surrounding macula. The short wavelength sensitive opsin, or S-opsin is the photopsin sensitive to the blue region of the visible spectrum between 400-500nm with a peak sensitivity at approximately 420nm.[5] These photopigments are found in the blue cone cells, which occur less frequently than the red and green cone cells and are scattered throughout the entire retina.

The combination of the red, green, and blue cone cells contributes to the ability to perceive color in brightly lit conditions with light levels greater than 3cd/m2 in a form of vision called photopic vision.[6] As photopic vision is derived from the combined response of the three cone cells and their respective photopigments, and relative contributions due their distribution and frequency within the retina, the peak efficacy of photopic vision occurs within the green region of the visual spectrum at approximately 555nm.[6] Photopsins, however, are not as sensitive to light as the rhodopsin found in the rod cells and do not respond to light levels below approximately 0.001 cd/m2.[5] This means that they are not sensitive to low-light condition and do not contribute to night vision, but it

also requires much higher light levels to oversaturate and bleach photopsins, allowing them to function in brightly lit conditions.

In intermediate light conditions with luminance values between 0.001 and 3 cd/m2 both the rods and cones can contribute to vision. This form of vision which uses all 4 visual photoreceptors is called mesopic vision and occurs naturally in twilight and moonlit conditions.[6]

As the rod cells occur throughout the entire retina, with the exception the fovea that contains primarily cone cells, they are the primary contributors to human peripheral vision. This peripheral vision occurs in the field of view between approximately 60° and 220° horizontally, and 60° and 110° vertically.[5] While rod cells do occur in the macula and contribute to central vision within the central 60° field of view, the lack of rod cells in the fovea and the central 2° field of view means that humans lose much of their visual acuity when using only scotopic vision.[3]

2.4. Non-Visual System

In addition to the visual system is a non-visual system that is primarily linked to intrinsically photosensitive retinal ganglion cells (ipRGCs) that occur in the outermost layer of the retina. This non-visual system of photoreceptors was discovered in 2002 in studies of rodent retinas.[8] These ipRGCs comprise about 1-5% of the retinal ganglion cells and are distributed throughout the retina.

IpRGCs have a photopigment called melanopsin that responds to the blue portion electromagnetic spectrum with a peak sensitivity of 480nm.[8] Unlike the photopigments used in the visual system, melanopsin is slow to respond to stimulus. Additionally, melanopsin occurs all throughout the ipRGCs. This differs from the photopigments in rods and cones which are located in one end of the cell, allowing them to collectively produce visual acuity. This means that ipRGCs respond primarily to general irradiance levels within the eye and respond most strongly to slow or still light for sustained periods. [8]

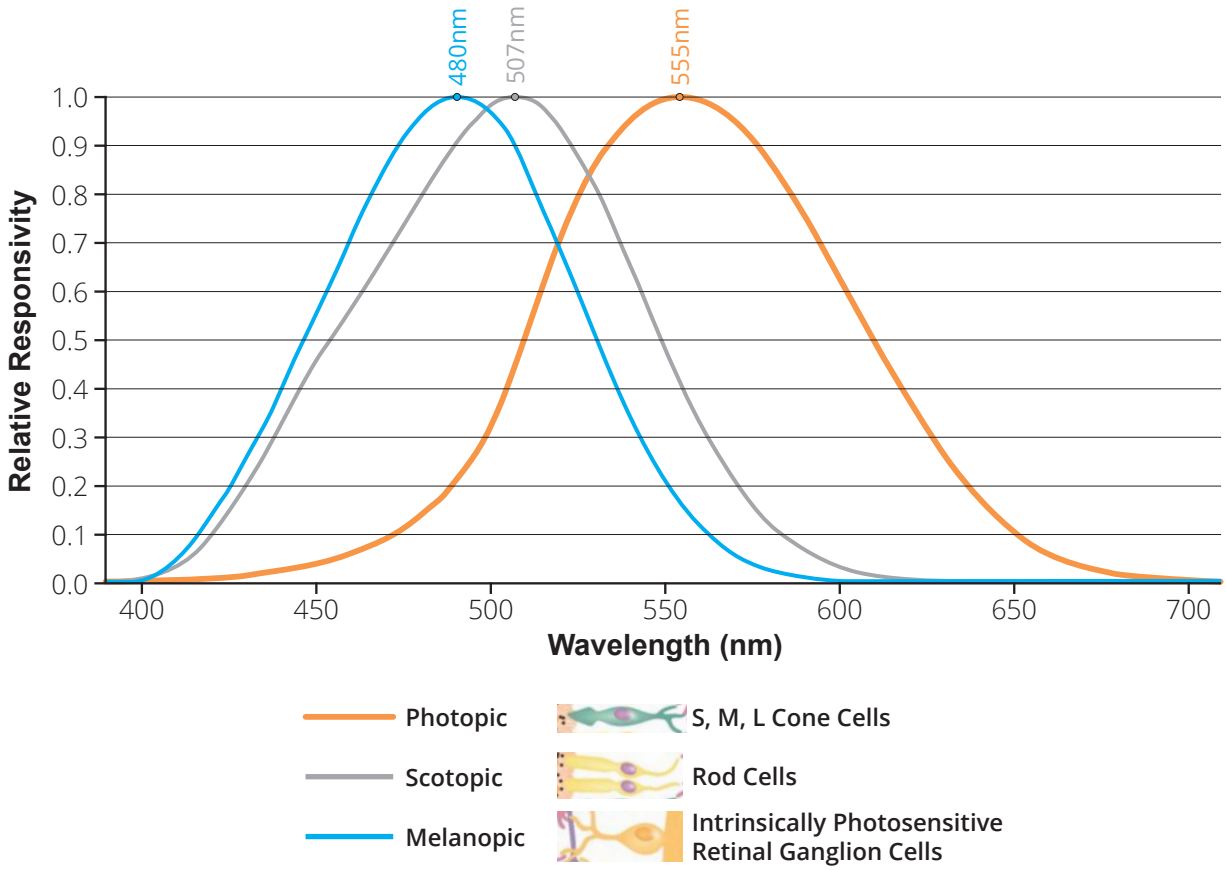


Figure 2.4. Relative responsivity of photopic vision, scotopic vision and melanopic sensitivity.

Being a non-visual system, these photoreceptors do not contribute anything

to visual acuity and instead are linked to a separate neural pathway called the retinohypothalamic tract which connects the ipRGCs directly to a tiny region in the brain in the hypothalamus, directly above the optic chiasm, called the suprachiasmatic nucleus (SCN).[9] The SCN is directly responsible for controlling circadian rhythms by regulating various neural and hormonal activities that affect how the body functions over a 24-hour period. While the full relationship between ipRGCs and the SCN is not yet known, multiple studies have linked stimulus to ipRGCs to many of the regulating functions of the SCN, including the production and regulation of melatonin and cortisol within the body. [7] Additionally, ipRGCs have been found to have an effect on pupillary reflex, which is how they were first discovered.[8]

2.5. Circadian Rhythms

Humans and many other organism experience physical, mental, and behavioral changes that follow a 24-hour cycle. These changes include a sleep-wake cycle, largely regulated by the level of melatonin and cortisol present in the body and other neuroendocrine systems including core body temperature and blood pressure. These cycles are called circadian rhythms and they are largely controlled by the SCN. The SCN is able to regulate the sleep-wake cycle through the production and suppression of melatonin from the pineal gland and cortisol from the adrenal gland. [9]

Melatonin – This hormone, produced by the pineal gland, induces physiological

responses which promote sleep including decreased body temperature and respiration rate.[9]

Cortisol - Often called the “stress hormone” due to its connection to the stress response, cortisol is a steroid hormone produced by the adrenal gland that regulates a wide range of processes throughout the body including metabolism, immune response, memory formation, and regulating blood pressure.[9] While the SCN does in part regulate the production of cortisol as it relates to circadian rhythms, it is also produced as a stress response and is particularly known for its part in the “flight-or-fight” response.

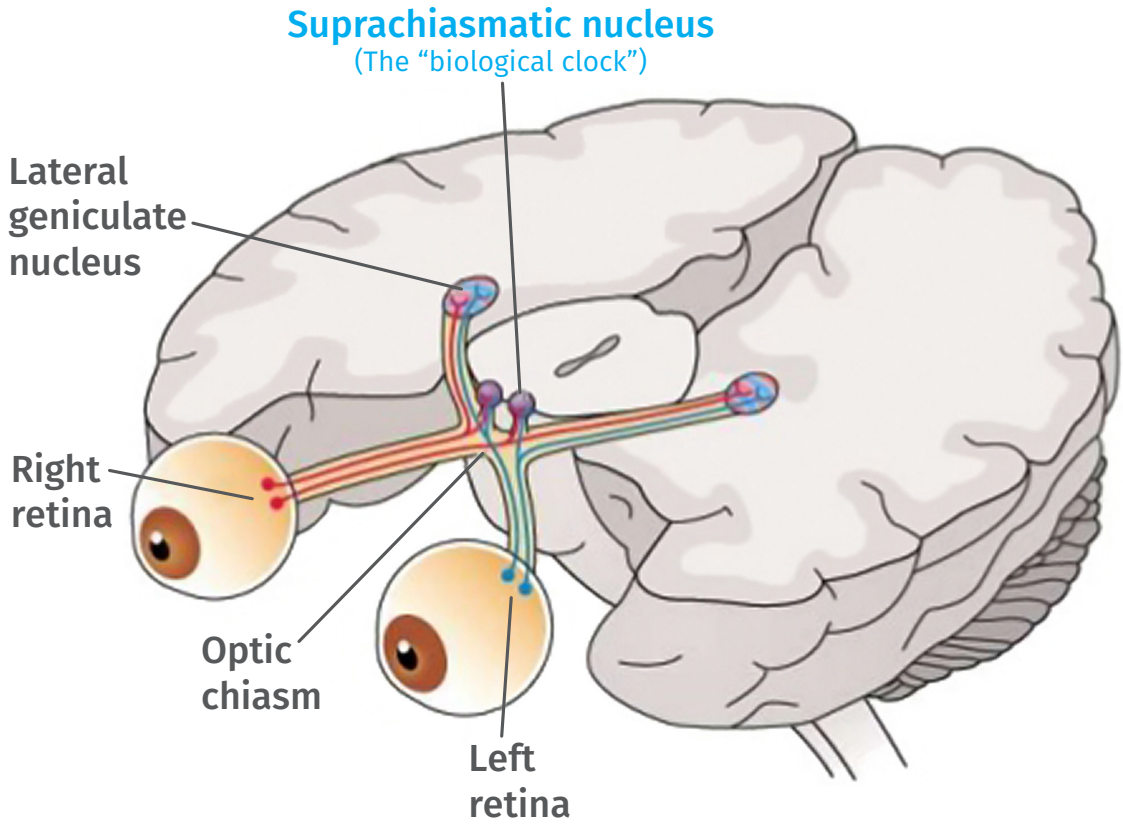


Figure 2.5. Visual and non-visual neural pathways.[10]

2.6. Melanopic Response

The SCN acts as the body's internal clock, regulating its circadian rhythms, however this clock does not actually run on a perfect 24-hour cycle. The actual timing for the cycle can be between 23.5hrs and 24.7hrs, averaging at proximately 24.2hrs in humans.[9] Due to this misalignment with day-night cycle, external stimuli are used to entrain the body's circadian rhythms to be in sync with the day-night cycle of local environment. ipRGCs play this role of by reacting to the presence of blue light in the environment and sending signals based upon its stimulus to the SCN which causes it to suppress or stimulate melatonin production and other endocrine functions at a rate corresponding to the stimulus. This response of ipRGCs to light stimulus and the subsequent link to the SCN is called melanopic response.

2.7. Circadian Lighting in the Built Environment

In order to make design decisions related to melanopic response we must first know what variables in the built environment have an impact on the circadian rhythm. Melanopic response is induced by a variety of factors including spectrum, intensity, duration, timing, photic history and age. Various studies have been done to determine how each of these factors effect melanopic response.

Spectrum – While it is currently unknown what the spectral sensitivity of the circadian systems is, it can be deduced that blue light near 480nm may have

a greater impact on the circadian system due to melanopsin being most sensitive to this frequency.

Intensity – Studies completed to determine how much light intensity is required to induce various levels of melatonin suppression are speculative at best due to them being completed in controlled environments that do not reflect the typical lighting conditions in everyday life. However, it is still worth noting that results showed that exposure to 200lx+ from a cool white (4100°k) fluorescent light induced full melatonin suppression, while lower brightness levels resulted reduced melatonin suppression and higher levels, near 550lx, resulted in phase shifting response.[11] This indicates that light intensity is a major factor in melanopic response.

Duration – A study exposing people to short intervals of bright light showed reduced melatonin levels after less than 10 minutes and increased levels less than 15 minutes after the light was extinguished.[12] This indicates that even short exposures to bright light under a minute can induce a melanopic response. Additionally, another study tested for a link between intensity and duration, and found that higher intensity required a shorter duration to achieve the same melatonin suppression response as a lower intensity at a longer duration.[13]

Timing – Studies have shown that exposure to light after sunset or before sunrise can cause a phase shift response in which a person circadian rhythm

becomes advanced or delayed.[9]

Photic History – Melanopic response sensitivity can be enhanced or suppressed based upon previous long duration exposure to lower or higher light levels respectively.[14] This means that the melanopic response of an individual can adapt to maintain circadian entrainment in environments with consistently lower or higher light levels.

Age – Various portions of the eye degenerate as people age. This includes the yellowing and darkening of the lens that can reduce the amount of blue light that can penetrate into the eye and suppress their melanopic response as compared to their younger counterparts.[15]

All of these factors must be considered when making design decisions within the built environment related to melanopic response. As artificial light sources, such as LEDs, are producing light that can affect melanopic response, careful consideration must be made upon the function, intensity, spectral output, and location of these lights in the built environment. That being said, the ideal strategy for maintaining a natural circadian entrainment to the day-night cycle will always be to maximize exposure to daylight during the day and minimize exposure to artificial sources of blue light during the night. Realistically though, this is not possible in all scenarios, so supplemental light exposure will likely be required to manage melanopic response in the built environment.

2.8. Equivalent Melanopic Lux

In order to evaluate circadian light within a given space, it is necessary to understand the units used to measure this light. Due to the high luminous efficacy of melanopic sensitivity as compared to photopic and scotopic vision, measuring circadian illuminance with absolute circadian lux results in values far higher than photopic lux under equal energy light. This scaling can cause confusion when working with these units, so to resolve this issue the units are converted to equivalent melanopic lux (EML).[16]

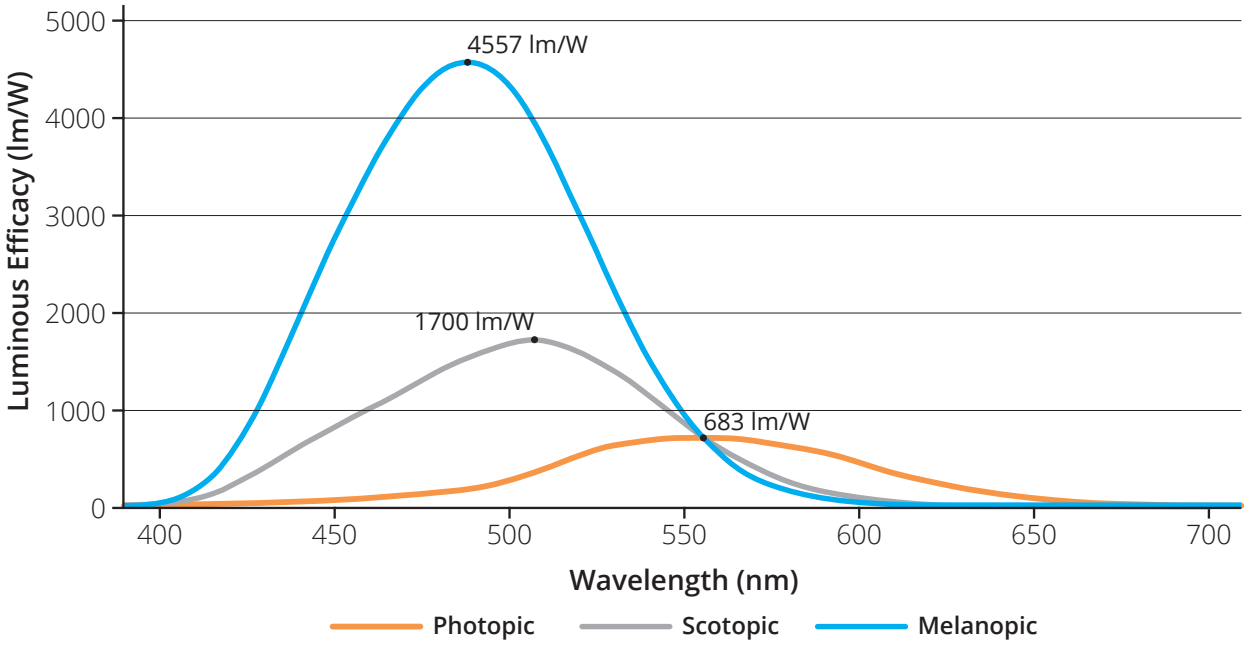


Figure 2.6. Photopic, scotopic, and melanopic luminous efficacy functions.

The EML unit was developed by Lucas et al by scaling the melanopic luminous efficacy curve to have an equal area beneath the curve as the photopic luminous efficacy curve.[16] This results in 1 EML equaling 1 lux under a theoretical equal energy white light. This one to one relationship between EML and photopic lux

allows for a linear relationship between the units that avoids issues of scaling and allows designers and researchers to work with values that are within a similar range as those used for typical lighting standards.

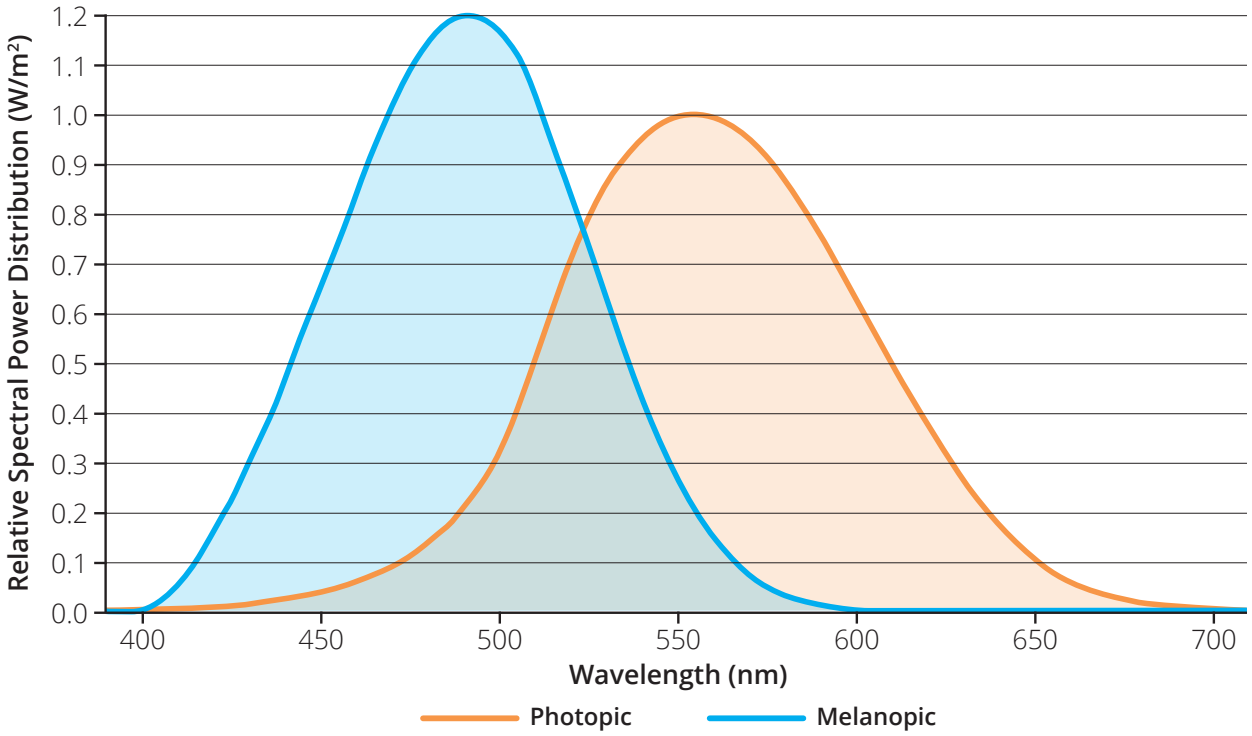


Figure 2.6. Photopic and melanopic curves scaled to have equal area under the curve.

2.9. Circadian Lighting Building Standards

The only current standard that exists with a requirement related to circadian lighting and melanopic response in the built environment is in the WELL Building Certification. Feature L03 of the Well 2.0 Building Certification requires a melanopic light intensity of at least 240 EML under electric light measured on the vertical plane at the occupant's eye level, maintained at least between 9am and 1pm in order to receive full credit.[17] This target was developed using current research and is intended to entrain the circadian pacemaker within

a 4-hour period. Partial credit is given for achieving at least 150 EML over the target time period and reduced requirements of 180 EML for full credit and 120 EML for partial credit are allowed when the building achieves feature L05 of the standard: “Enhanced Daylight Access”.[17]

While no other standards exist that pertain directly to circadian lighting and melanopic response, many requirements for daylight in green building rating systems such as LEED, Living Building Challenge, and Green Globes do achieve the goal of increasing access to natural daylight in the workplace and may inherently enhance the circadian lighting quality as well.

3. Methodology

The methodology for this study was comprised of 3 parts: field measurements, occupants surveys, and simulations. The initial analysis of circadian lighting within existing offices today was completed through a series of case studies examining 3 existing offices within Seattle. These case studies consisted of a quantitative analysis of the circadian lighting at a selection of workstation within each office and qualitative analysis through a workplace lighting survey distributed to each offices' occupants. These case studies were then used to identify various architectural parameters for further study through simulation. Circadian lighting simulations were used to isolate the effect of these various architectural parameters to begin to identify some potential guidelines for use by designers to better utilize daylight for circadian stimulus. This chapter defines the methodology used to analyze the circadian lighting of the existing offices and to create accurate simulations for further study.

3.1. Circadian Lighting Analysis through HDR Photography

This method for measuring melanopic illuminance was developed by Jung B. and Inanici M. in their research paper: "Measuring circadian light through High Dynamic Range Photography" and will be summarized in section.[18] In order to measure and analyze the circadian light within an individual's field of view at a workstation HDR (High Dynamic Range) photographs were generated of each selected workstation by combining multiple LDR (Low Dynamic Range) photographs taken with a Nikon D40X DSLR camera with a Lens Baby 185°

Circular Fisheye Lens. Each image had to be corrected for various aberrations in the capture process and the software used to generate the images had to be calibrated to adjust for this camera's RGB response curve in order to generate reasonably accurate readings. Two additional tools were required for this calibration: a Konica Minolta LS-110 luminance meter to take luminance measurements of the target at the center of the image, and a Konica Minolta CL-200A illuminance color meter to gather CIE XYZ color data at the camera lens during each capture. Each image had to be processed through eight adjustments before a final photopic and melanopic luminance calculation images could be produced.

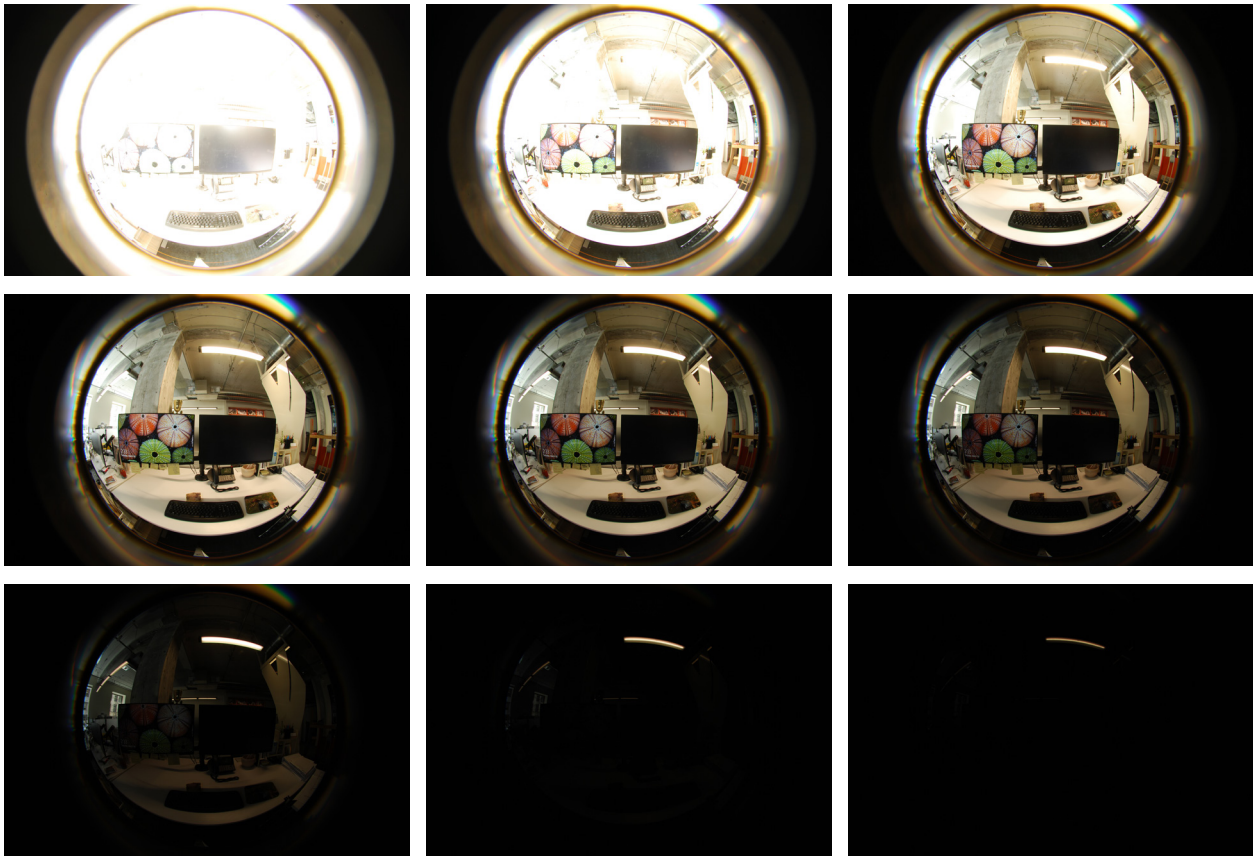


Figure 3.1. Multiple pictures taken in succession with exposure times ranging from 30 seconds to .001 seconds.

3.1.1. Crop

The photographs produced with Nikon D40X DSLR camera with Lens Baby 185° Fisheye lens included extraneous data that is both outside the scope of analysis and would create significant errors in the final calculations. As the final image for the quantitative analysis requires a 180° fisheye field of view, the outer 5° of each image and internal lens reflections needed to be cropped of each image. Multiple photographs taken with a target set at 5° increments from the camera's central point of view allowed for the creation of a measurement overlay to determine what portions of the image were within 180° of the camera's field of view. This overlay was then used to create an image mask that was applied to each photograph before further adjustments were applied.

3.1.2. Resize

The Nikon D40X CCD produces an image with a maximum size of 3872 x 2592 pixels. The 180° cropped fisheye image only used a central portion of this total image size. For ease and consistency of later processing steps, each image was resized to 2000 x 2000 pixels.

3.1.3. Conversion to Equidistant Fisheye

The Lens Baby 185° Fisheye lens does not produce a perfectly equidistant fisheye image. The image produced by this lens has a near equisolid angle projection for the central 70% of the image, then distorts and compresses the

outer 30% of the image. To account for this distortion and prevent significant miscalculations for any light source(s) that may appear in this outer 30% of the image an algorithm was applied to each image to extrapolate a true equidistant fisheye image using a python script.

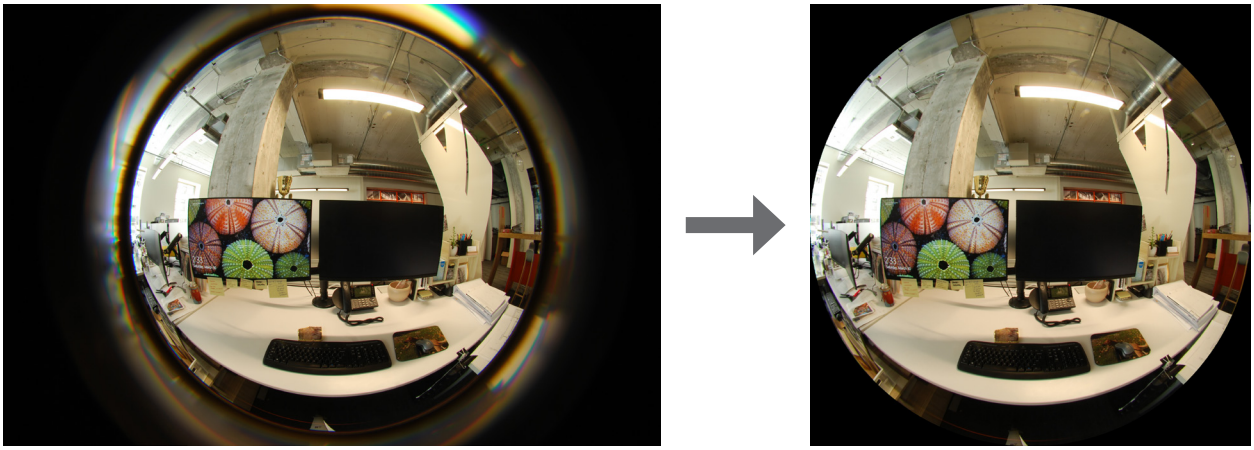


Figure 3.2. Initial post-processing including cropping, resizing, and conversion to equidistant fisheye projection (original image left, processed image right).

3.1.4. Camera Response Curve and Luminance Calibration

The software used to generate the HDR images from multiple LDR exposures was Photosphere. In order to generate an HDR image, the camera's response curve must first be calibrated. Due to multiple variables including light loss through the lens, gamma correction, tone mapping, and more the RGB values captured by the camera have a non-linear relationship with reality. Photosphere uses a technique called radiometric self-calibration that uses a polynomial function to compute this relationship and generates a response curve specific to the camera. In order to generate an accurate response curve a series of exposures of a day-lit scene with a wide range of luminance values was taken

then processed through Photosphere. Once the initial response curve was created it was then calibrated to match luminance reading taken from a gray-scale target at the center of the scene using a Konica Minolta LS-110 luminance meter set adjacent to the camera. This final calibration reduces the error in luminance values calculated through the HDR image to an acceptable range.

3.1.5. Vignetting Correction

The Lens Baby 185° Fisheye lens creates a light fall-off (vignetting) in pixels on the outer periphery of the image due to the structure of the lens. To correct for this reduction in luminance values in the periphery of the image a mask was created using a polynomial function generated by taking luminance readings from multiple HDR images of a gray-scale target at 5° increments and calculating the variance of the readings as compared to the measured luminance using a Konica Minolta LS-110 luminance meter placed in adjacent to the camera. These measurements and their variances were entered into excel and charted to generate the polynomial trend-line that was used to generate the 180° vignetting correction mask of the same resolution of the HDR images. This mask was applied to each image using the pcomb Radiance function which combines the luminance values of two images on a pixel by pixel basis.

3.1.6. Hemispherical Projection

In order to capture luminance data that can be verified and calibrated against measured values from an illuminance meter, the incident light captured by the

equidistant fisheye image must be adjusted to match the hemispherical (cosine corrected) projection used by the illuminance meter. The software hdrscope was utilized to compute the cosine correction of the equidistant projection and transform the equidistant projection to hemispherical projection by using the pinterp Radiance command. This command rearranges the pixels from the input pictures to produce a reasonable estimate of the desired view, in this case interpolating an equidistant projection to a hemispherical projection.

3.1.7. Illuminance Calibration

To ensure that all the light energy is accounted for in the cosine corrected HDR images, an illuminance calibration is required. Hdrscope is utilized in this process to calculate the total measured illuminance value in the cosine corrected HDR image and then adjust the output to match a measured illuminance reading from an illuminance meter placed at the face of the lens at the time of the image capture.

3.1.8. Color Calibration

Digital cameras use an imaging sensor called a CCD (charge-coupled device) to convert light into an electronic output. The spectral sensitivity of the CCD can vary widely between camera brands, models, and individual units. Due to this variance, the HDR images collected with any individual camera must be calibrated to correct for over or under exposed colors as compared to the true color values of the scene. If this calibration is not completed, measured values

of equivalent melanopic lux can be very inaccurate.

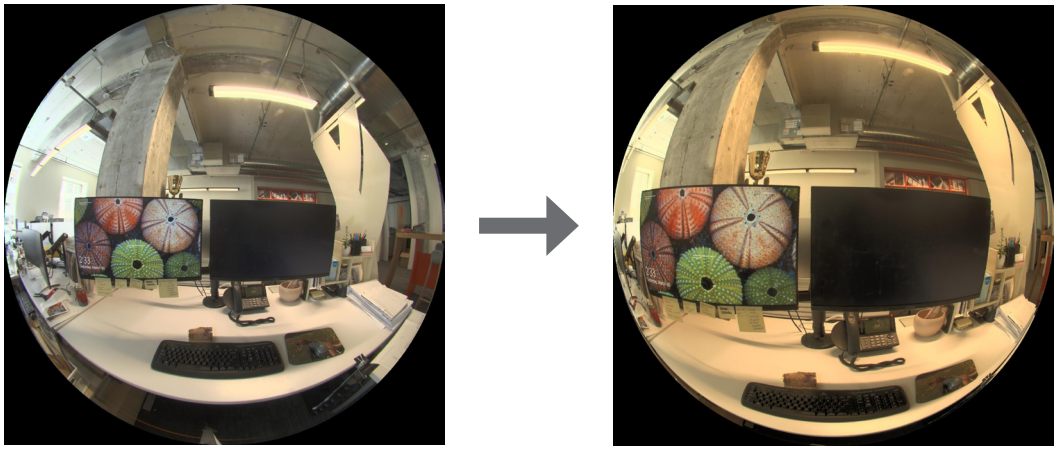


Figure 3.3. Initial HDR image generated from series of processed exposures (left). Final processed HDR image for analysis (right).

In order to color calibrate the HDR images, a color correction equation for each of the 3 CIE XYZ color channels of the image is applied. Over 50 HDR photos were taken of scenes with varying color and illuminance to create a data set large enough to determine a linear regression equation for each channel that can be used for color calibration. Each image was then calibrated with the 7 steps listed above, before a radiance script was used to isolate each of the XYZ color ranges within each image. The software hdrscope was then used to calculate the illuminance in each isolated color range of the image. These CIE XYZ color channel values collected by the camera are then compared to the values collected by a Konica Minolta CL-200A illuminance color meter placed at the face of the lens at the time each image as captured. The linear regression equation derived from the variance between the collected and measured values is then ready to be used to color calibrate the HDR images

used for circadian lighting analysis.

3.1.9. Photopic and Melanopic Analysis

The final calibrated HDR images can be analyzed in hdrscope through multiple process. The two primary processes used in this study were the false color visualization, which coverts the image into a color gradient that represents the luminance values within the image, and the luminance distribution tool, which charts the luminance values present in the image and identifies the minimum, maximum, mean, and median luminance values. Since the final image is a hemispherical fisheye projection, the mean luminance value in the circular portion of the fisheye image can be multiplied by pi to determine the illuminance value of the image.

In order to measure the melanopic illuminance present in the calibrated HDR images, the image must be processed to isolate the circadian spectral range. This is completed through the use of a radiance script which uses a formula developed by Jung B. and Inanici M.[18] to proportionally adjust the RGB values of the image to match the equivalent melanopic spectral range. The now circadian calibrated HDR image can be processed in hdrscope in the same manner as the original for both a false color visualization of the equivalent melanopic luminance, and the equivalent melanopic luminance distribution. The mean equivalent melanopic luminance is then multiplied by pi to determine the equivalent melanopic illuminance of the image in EML.

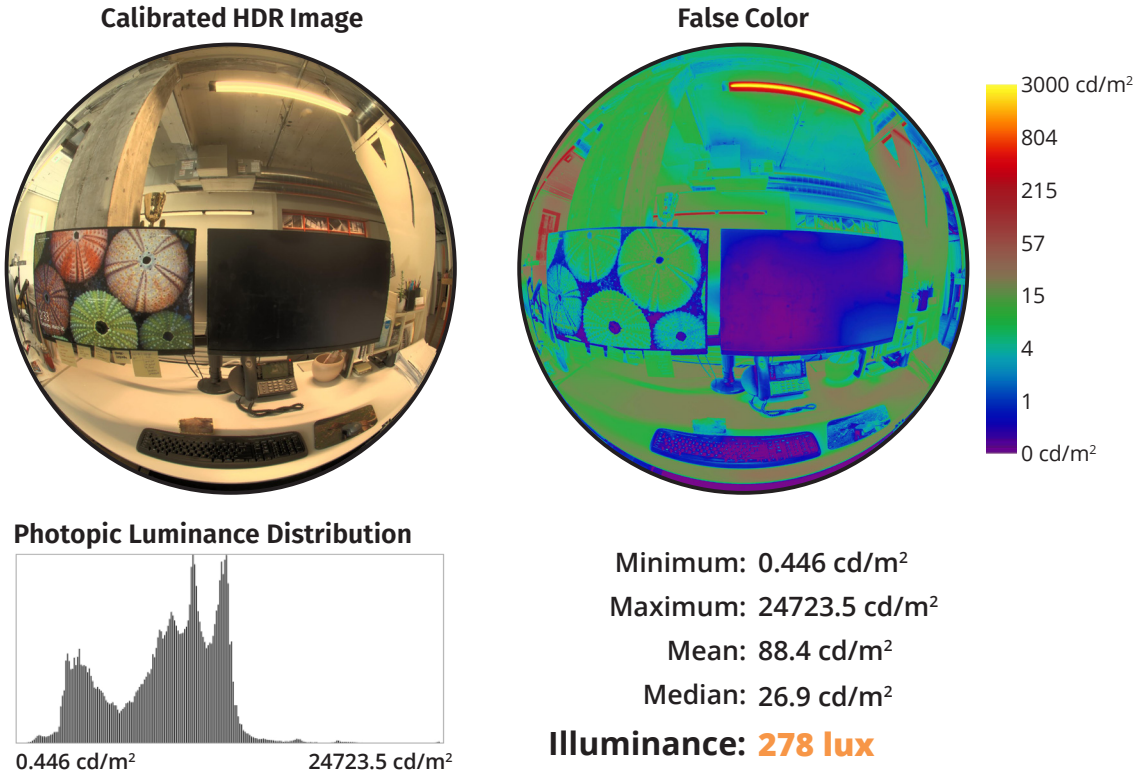


Figure 3.4. Example of photopic analysis of an HDR image.

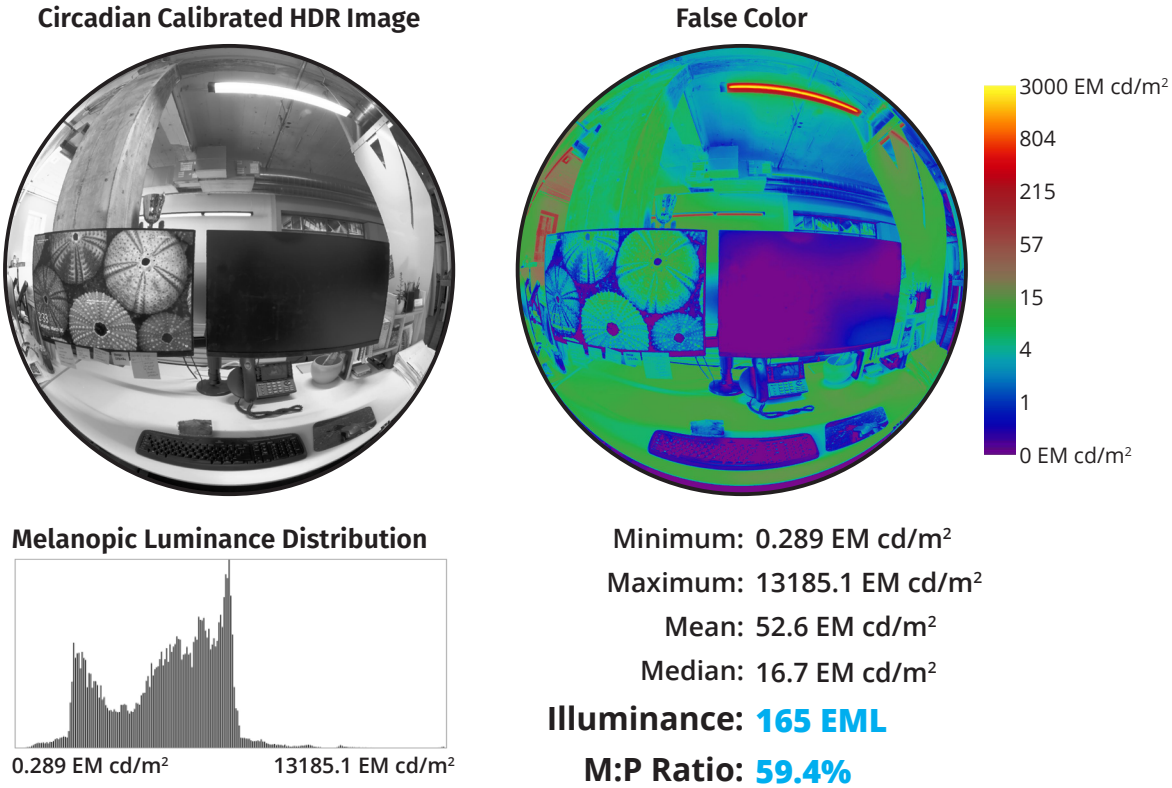


Figure 3.5. Example of circadian analysis of an HDR image.

3.2. Workplace Lighting Survey

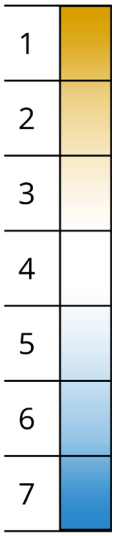
For the qualitative study of lighting of each of the case studies, a digital workplace lighting survey was distributed to the occupants. This survey consisted of 12 questions that were designed to identify various parameters of each participant's experience within the office and how their experience affects their individual alertness and visual comfort, as seen in figure 3.6.

1. When in the office, do you spend most of your time working from your workstation? (50%+of your time in the office)
   - ○ Yes
   - ○ No
2. Where is your workstation? (Refer to seating chart)
3. When do you feel sleepy while working at your workstation? (Check all that apply)
   - ○ Mornings
   - ○ Afternoons
   - ○ Evenings
   - ○ Never
   - ○ Overcast Days
   - ○ Sunny Days
4. When do you feel alert while working at your workstation? (Check all that apply)
   - ○ Mornings
   - ○ Afternoons
   - ○ Evenings
   - ○ Never
   - ○ Overcast Days
   - ○ Sunny Days
5. How comfortable is the lighting of your workstation during the day?
   - ○ 1 - Very Uncomfortable
   - ○ 2 - Uncomfortable
   - ○ 3 - Somewhat Uncomfortable
   - ○ 4 - Neutral
   - ○ 5 - Somewhat Comfortable
   - ○ 6 - Comfortable
   - ○ 7 - Very Comfortable
6. How comfortable is the lighting of your workstation during the evening?
   - ○ 1 - Very Uncomfortable
   - ○ 2 - Uncomfortable
   - ○ 3 - Somewhat Uncomfortable
   - ○ 4 - Neutral
   - ○ 5 - Somewhat Comfortable
   - ○ 6 - Comfortable
   - ○ 7 - Very Comfortable

7. Can you see the sky while working at your workstation?
   - ○ Yes
   - ○ No

8. During the day, is your workstation primarily lit by daylight or electric light?
   - ○ 1 - All Electric, No Daylight
   - ○ 2 - Mostly Electric, Minimal Daylight
   - ○ 3 - Mostly Electric, Some Daylight
   - ○ 4 - Half Electric, Half Daylight
   - ○ 5 - Mostly Daylight, Some Electric
   - ○ 6 - Mostly Daylight, Minimal Electric
   - ○ 7 - All Daylight, No Electric

9. Is the light at your workstation during the day warmer or cooler in color? (Refer to color chart)
   - ○ 1 - Very Warm
   - ○ 2 - Warm
   - ○ 3 - Somewhat Warm
   - ○ 4 - Natural White
   - ○ 5 - Somewhat Cool
   - ○ 6 - Cool
   - ○ 7 - Very Cool



10. Is the light at your workstation during the evening warmer or cooler in color? (Refer to color chart)
   - ○ 1 - Very Warm
   - ○ 2 - Warm
   - ○ 3 - Somewhat Warm
   - ○ 4 - Natural White
   - ○ 5 - Somewhat Cool
   - ○ 6 - Cool
   - ○ 7 - Very Cool

11. How bright is your workstation during the day?
   - ○ 1 - Underlit
   - ○ 2 - Dim
   - ○ 3 - Somewhat Dim
   - ○ 4 - Just Right
   - ○ 5 - Somewhat Bright
   - ○ 6 - Bright
   - ○ 7 - Overlit

12. How bright is your workstation during the evening?
   - ○ 1 - Underlit
   - ○ 2 - Dim
   - ○ 3 - Somewhat Dim
   - ○ 4 - Just Right
   - ○ 5 - Somewhat Bright
   - ○ 6 - Bright
   - ○ 7 - Overlit

Figure 3.6. Workplace lighting survey.

Completed surveys were collected and the responses to each question compared to the relevant parameter in each office to determine if any rough correlation could be made between the responses and that parameter.

3.3. Circadian Lighting Simulations

Circadian lighting simulations were created to test various architectural parameters to better understand their effect on the circadian potential within a space. These simulations were completed using 3d models of offices created in Rhino, then loaded into a lighting simulation software specifically designed to simulate and measure the EML values within the model. All simulations were completed with daylight only located in Seattle, WA. Simulations for each included a set of shared static base parameters including date and time of simulation, sky conditions, material selection, and sensor grid position and layout. Results from the simulations were then post-processed to create visualizations and analyze the data.

3.3.1. ALFA – Adaptive Lighting for Alertness

Circadian lighting simulations were completed using a new tool developed by Solemma called ALFA.[19] Unlike other lighting simulation software, such as Diva which was also developed by Solemma, ALFA (Adaptive Lighting for Alertness) is specifically designed to calculate circadian lighting levels. It does this using spectral raytracing with 81-color-channel 180° fisheye sensors placed on a vertical plane. For accurate daylighting results, ALFA uses spectrally accurate

skies generated using the radiative transfer library libRadtran. Skies can be generated for any location on the earth and any time of year with physically accurate clear, hazy, overcast, and heavy overcast sky cover conditions. Additionally, ALFA uses a library of spectrally accurate materials based on spectrophotometric measurements of real architectural materials and glazing types from the international glazing database.

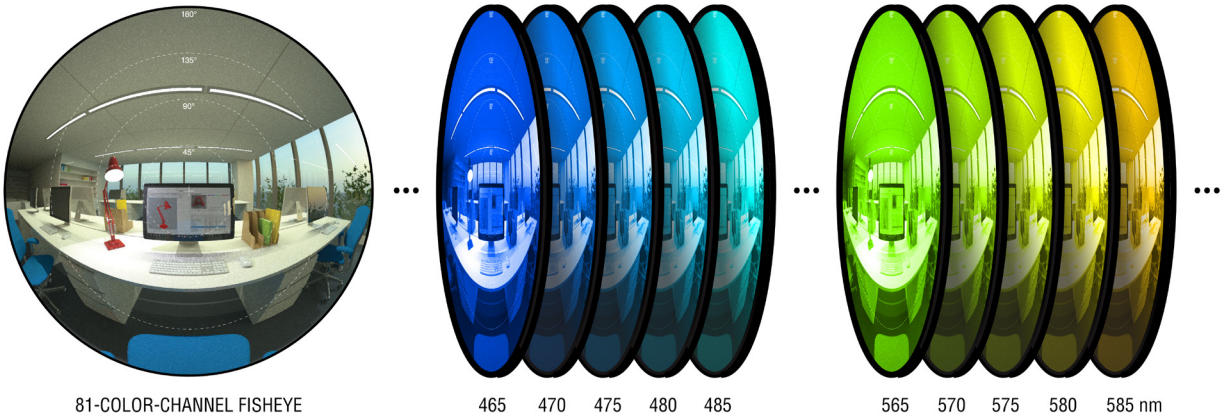


Figure 3.7. 81-color-channel fisheye generated in ALFA.[19]

3.3.2. Sky Selections

Seattle, WA was selected for the location for simulation as the case studies were all located within Seattle. By completing the simulation with the same climate and location as the case studies, it was possible to verify the validity of the simulations by comparing simulated data with the data collected in the case studies. Skies generated for simulation were then selected based upon conditions within Seattle.

As with typical daylighting design practice, the dates selected for simulation

were the summer and winter solstices (June 21st and December 21st respectively), and the fall equinox (September 21st). This selection of dates covers the full range of the sun's movement through the year with the upper and lower extremes, and the midpoint. 9am, 11am, and 1pm were selected for simulation as the goal for maximizing circadian stimulus necessitates providing that stimulus during the early hours of the day to suppress melatonin production for maintained alertness throughout the day. The hours between 9am and 1pm were selected specifically as this corresponds with the targeted time period from the WELL building standard.

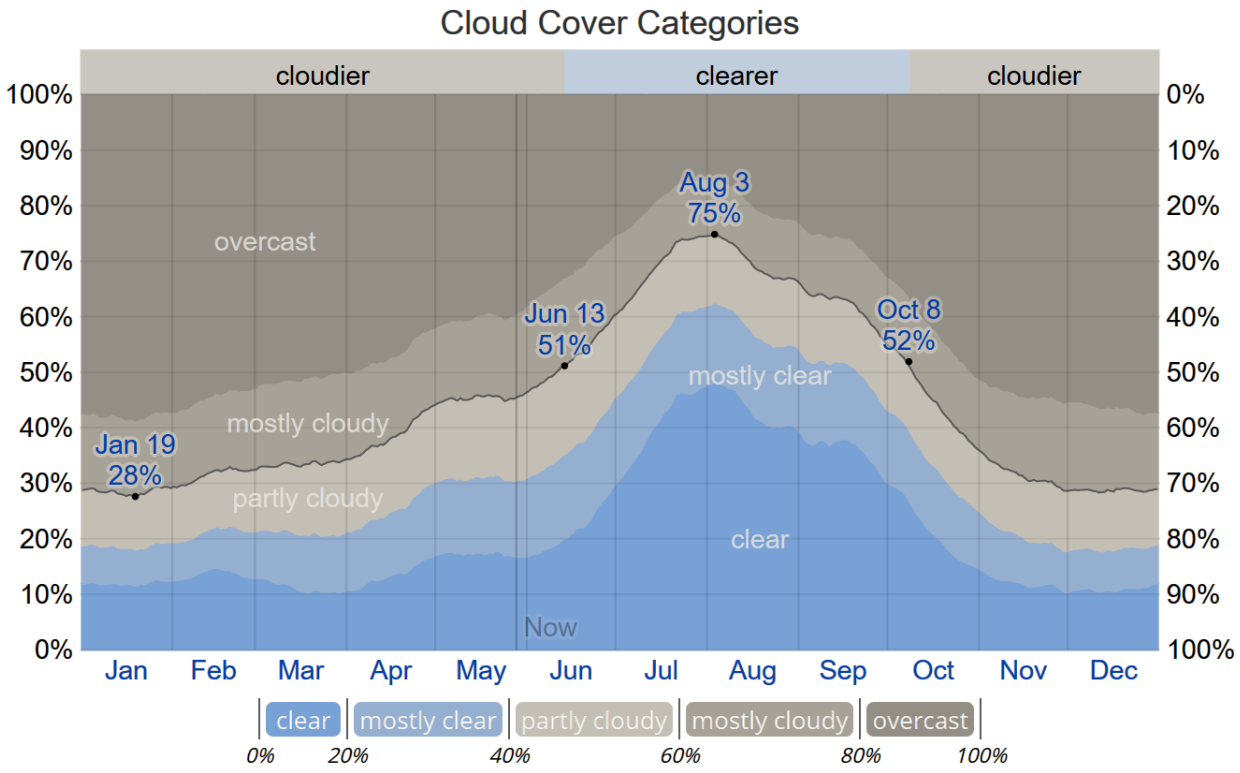


Figure 3.8. Seattle cloud cover.[20]

Cloud cover conditions were selected to simulate changing weather conditions within Seattle. Clear and mostly clear conditions in Seattle are most common between the months of June and October, intermediate conditions (mostly and partly cloudy) are most common from April into early July and from late September into late October, and overcast conditions are most common from November through to the end of March.[20] From this it was determined that June simulations would use a clear sky model, September simulations would use a hazy or intermediate sky model, and December simulations would use an overcast sky model.

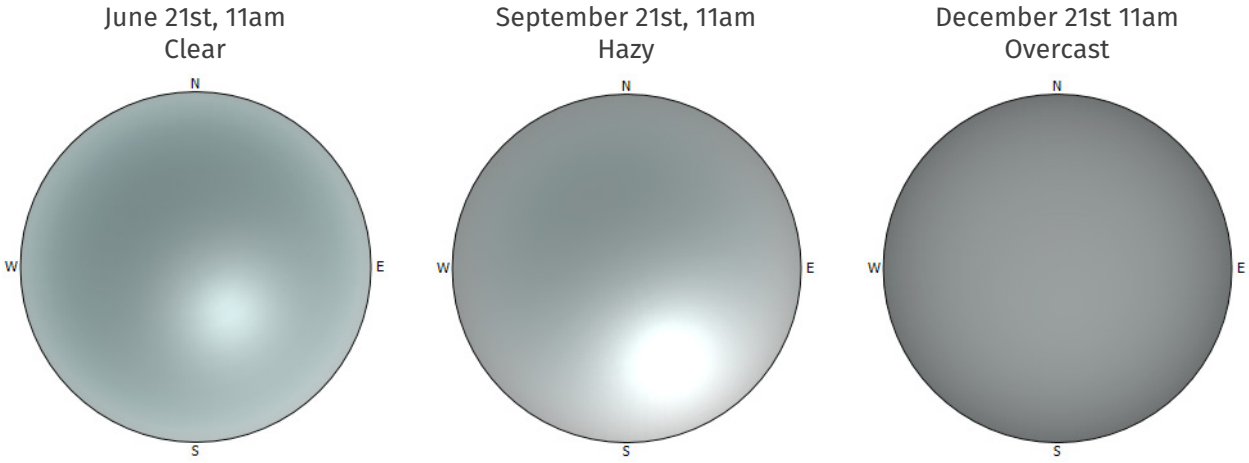


Figure 3.9. ALFA skies generated for simulation.

3.3.3. Material Selections

While material spectral qualities can play a potentially large roll in the quantitative analysis of circadian light, this was not a targeted parameter being measured in this study. Due to this, simple grayscale materials with reflectance values typical to their location were selected from the ALFA

material library for simulation. Within the simplified hypothetical office model ceilings were “white painted room ceiling” with 82.2% photopic reflectance and 77.4% melanopic reflectance, walls were “white painted room walls” with 81.2% photopic reflectance and 78.3% melanopic reflectance, and floors were “interior flooring” with 38.1% photopic reflectance and 38.4% melanopic reflectance. Glazing materials used for simulation were “double IGU clear tvis 70%” with a photopic and melanopic transmittance of 70.1%. Shading devices, when simulated, were set to match interior walls. Material selections for the simulation validation model were selected to match observed materials within the case study office as closely as possible with the available materials from the ALFA material library. Surrounding context buildings, when present in the simulations, were set to “aluminum grey exterior cladding” with 47.6% photopic reflectance and 46.6% melanopic reflectance.

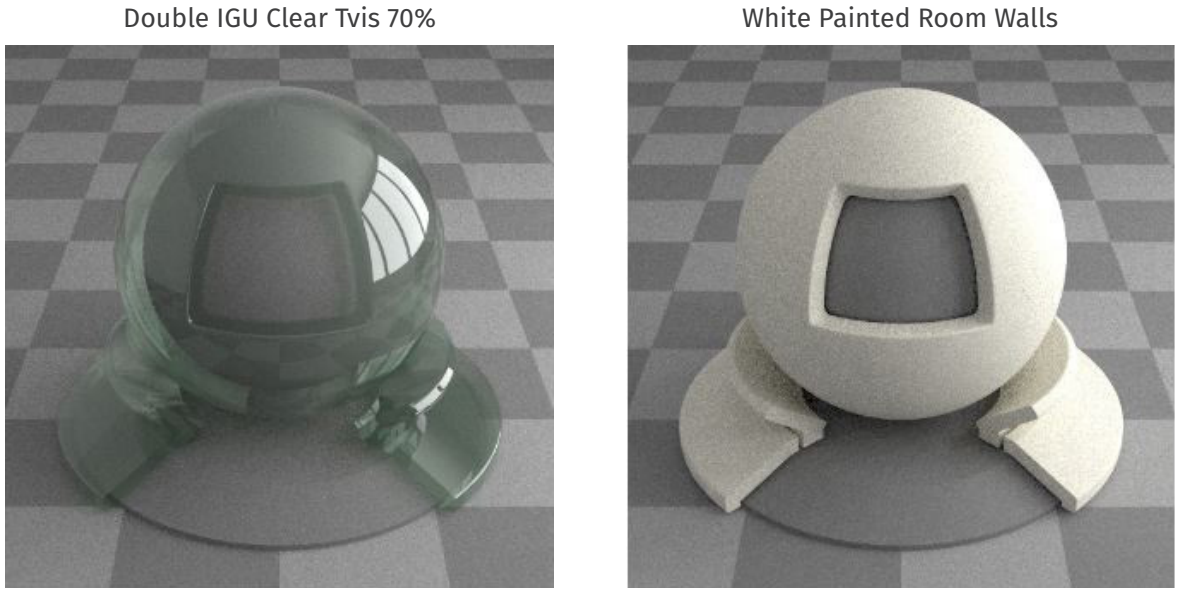


Figure 3.10. Visualization of ALFA materials used for simulation

3.3.4. Sensor Grid Layout

Sensor locations were set onto a 2ft by 2ft grid with a 1ft offset from interior walls. This layout allowed for an optimal resolution for data collection, while maintaining a high simulation speed. Each sensor location was populated with 9 sensors, one workplane sensor placed horizontally at 30” above floor finish, and 8 view sensors placed vertically 48” above floor finish oriented to capture a full 360 degrees of view angles in 45-degree increments.

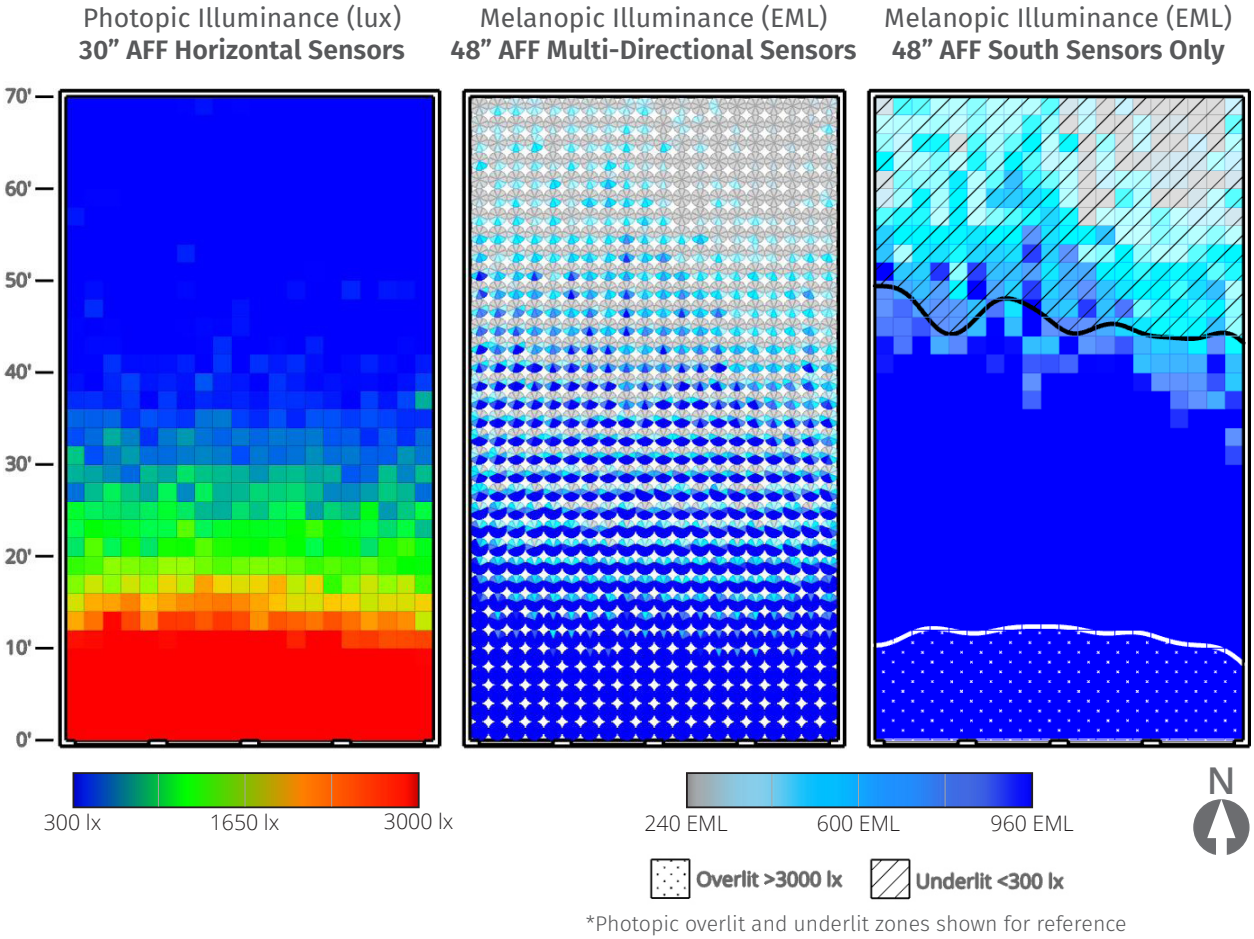


Figure 3.11. Example of plan view visualizations of 2’x2’ sensor grid, photopic and melanopic color gradient scales, and overlaid photopic underlit and overlit zones for analysis.

3.3.5. Target Photopic and Melanopic Illuminance Values

For workplace environments, typical targeted photopic illuminance values for daylighting, as measured on the horizontal plane at the height of the work surface, are 300-3000 lux. Measured values less than 300 lux are considered underlit and an indicator of required supplemental electric lighting, while measured values greater than 3000 lux are considered overlit and an indicator of potential glare and visual discomfort. These targets were used in the simulations to identify and compare measured photopic illuminance values to measured melanopic illuminance values.

Targets for melanopic illuminance values were set to correspond with the WELL building standard. Exposure to 240 EML sustained over a 4-hour period results in full melatonin suppression and a phase shift response in an individual's circadian rhythm.[21] Due to the nature of melanopic sensitivity, there is no potential for glare or discomfort due to high levels of melanopic illuminance. However, as research has shown a correlation with increased light intensity to a corresponding increase in circadian entrainment, a maximum target value of 960 EML (4 times the WELL standard target) was used to analyze the gradient of circadian lighting potential within the simulations.[11] Due to the lack of glare potential in circadian lighting, simulation results for photopic illuminance were overlaid onto the melanopic illuminance results visualizations to analyze their relationship.

3.3.6. Post-Processing

Data from each simulation was exported from ALFA in CSV (comma separated value) format. This output organizes the data by sensor point location with world XYZ coordinates within the model and XYZ vector definition of the orientation of the sensor. Each sensor includes data on collected photopic and melanopic illuminance values, the melanopic to photopic ratio, and collected illuminance values for each of the 81 spectral color channels. Once exported, excel was utilized to organize the data for further post-processing.

To analyze the data and create visualizations of each simulation a Grasshopper script was generated that could place shaped 2D planes at sensor locations and apply a color to each that corresponds to color gradient to represent photopic and melanopic illuminance values. This script was also utilized to calculate average illuminance values, percentage of area above target values, and other useful metrics for analysis. This script can be found published on GitHub: https://github.com/Nalten88/Circadian-Lighting-Design-ALFA-Visualization-Grasshopper-Script

Document: HypOffice_70ft_Punched_8ft_.40wwr.3dm
Variant: 092111_Hazy_South

WORKPLANE SENSORS

ptX	ptY	ptZ	dirX	dirY	dirZ	EML	Lux	M/P	380	385	390	395	400
19	-34	4	0	0	1	5050.38	5167.8	0.97728	0.00817	0.00747	0.01354	0.01287	0.02852
19	-32	4	0	0	1	4883.54	5098.9	0.95776	0.00729	0.00673	0.01225	0.01167	0.02603
19	-30	4	0	0	1	4102.16	4340.99	0.94498	0.00546	0.00507	0.00935	0.00907	0.02059
19	-28	4	0	0	1	3043.17	3272.67	0.92987	0.0038	0.00354	0.00656	0.0064	0.01461
19	-26	4	0	0	1	2736.05	2979.25	0.91837	0.00284	0.00269	0.00507	0.0051	0.01201
19	-24	4	0	0	1	2392.1	2627.06	0.91056	0.00215	0.00206	0.00395	0.00405	0.00978
19	-22	4	0	0	1	1556.23	1720.01	0.90478	0.00126	0.00121	0.00231	0.00239	0.00591
19	-20	4	0	0	1	1633.2	1852.23	0.88175	0.00098	0.00097	0.00192	0.00209	0.00538
19	-18	4	0	0	1	1179.97	1352.76	0.87227	0.00061	0.00061	0.00123	0.00137	0.00363

Figure 3.11. CSV data export from ALFA.

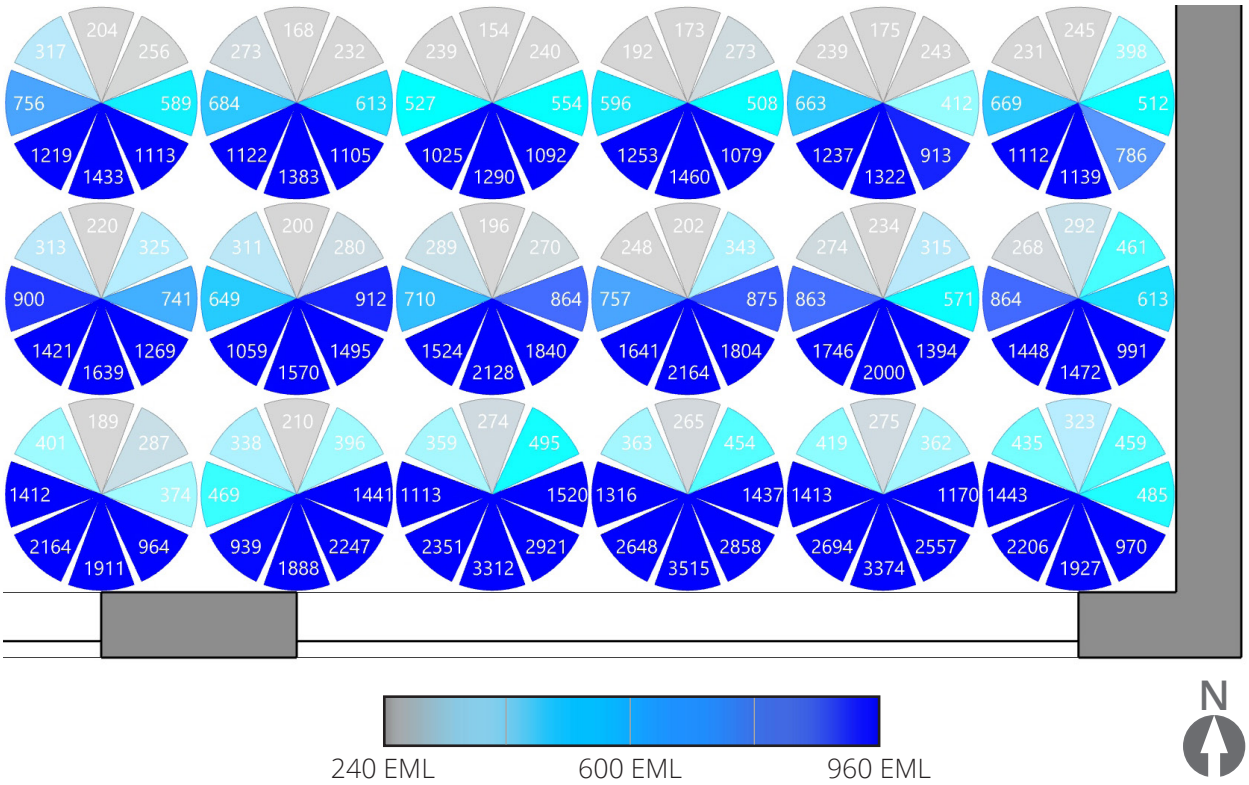


Figure 3.12. Visualization of multi-directional view sensors with EML color gradient applied.



Figure 3.13. Visual representation of multi-directional view sensor.

4. Circadian Lighting Case Studies

To better understand the current status of circadian lighting in office spaces today, case studies were completed analyzing the melanopic illuminance at workstations in 3 office spaces in Seattle along with a qualitative study through a survey of each office's occupants. Offices selected for study represent a range of daylighting design strategies and office layouts. Multiple sets of HDR images were generated for each workstation to isolate the effect of electric lighting strategies. Results from these case studies provided guidance towards identifying various architectural attributes for further study in simulations.

4.1. Case Study Selections

The three offices selected for study were the Ankrom Moisan Architects office located in the Central Business District in downtown Seattle, the Weber Thompson office in South Lake Union, and the UW Tower in the University District. The Ankrom Moisan Architects office is located in 1505 5th Ave which was constructed in 1926. When Ankrom Moisan moved into the building in 2016, tenant improvements were completed to create a contemporary open office layout in levels 2 and 3 of the building. Workstations were placed at the periphery of the office oriented to face parallel to the large punched windows in pods up to 4 workstations deep from the window. This layout is typical of recent daylighting standards and is intended to maximize access to daylight and exterior views for the occupants, while minimizing visual discomfort due to glare. No shading devices are installed on the exterior windows of this office.

This may be due to the reduced access to daylight created by the surrounding buildings in downtown Seattle. Artificial lighting in the office was provided primarily by semi-direct linear LED pendants with a color temperature of 3500K.



Figure 4.1. 1505 5th Ave, Ankrom Moisan Architects Office on levels 2 and 3.[22]

The Weber Thompson office is located in The Terry Thomas building at 225 Terry Ave. N, was designed by Weber Thompson and constructed in 2008. The building is LEED Gold certified and designed with a focus on daylighting with a central courtyard and continuous glazed window wall on most of the exterior.

The Weber Thompson office, located on level 2, is arranged in an open office layout with low 48” partitions between workstations. Most workstations are located in the center of the narrow floor plates, leaving a circulation zone at the periphery. Occupants can arrange their own workstation to orient themselves in the space as they please, resulting in a variety of orientations in relation to the windows in the space. Shading devices include segmented awnings and automatic exterior blinds on the South facing windows. Artificial lighting in the office is primarily provided by indirect florescent linear pendants with a color temperature of 3500K.



Figure 4.2. The Terry Thomas, Weber Thompson Office on level 2.[23]

The UW Tower was constructed in 1975 and does not present a daylight centric design focus. Recent renovations on select floors of the tower have been completed in order to update the office layouts and install a “Human Centric” LED lighting system from PlanLED. The new lighting system includes LED troffer lights with adjustable dimming and color temperature controlled by a central computer, and high performance LED task lights with customizable color temperature and brightness modes that can be selected by the user.



Figure 4.3. UW Tower[24]

Floors selected for study were levels O-3 and C-1. Level O-3 is a large floor plate

with punched windows on the West and North faces and includes the recently renovated lighting system set to 4000K, but dimmed down to 50%. Workstations are arranged in partial cubicles with 54” partitions and occupants are able to arrange their workstation as desired. Most workstations are oriented to face towards or away from exterior windows. Level C-1 is a smaller office with west facing punched windows that still uses the original florescent troffer lighting with a color temperature of 3500K from the tower’s construction. Workstations on this level are arranged in cubicles with tall 70” partitions. On both floors of the case study, manual roller shades were installed on the exterior windows.



Figure 4.4. PlanLED Epikos High Performance Workstation LED Task Light[25]

4.2. Case Study 1 - Ankrom Moisan Office

The Ankrom Moisan case study was conducted on March 30th and April 14th. The March 30th study occurred in the afternoon around 1pm with clear skies and a measured global solar irradiance of 520 W/m^2, while the April 14th study

occurred in the morning around 10am with overcast skies and a measured global solar irradiance of 211 W/m^2.[26] Workstations for study were identified in 2 zones, Zone A on the northeast side of the office and Zone B on the southeast side of the office. In order to analyze the change in melanopic illuminance as distance from the window increased, workstations for study were organized in increasing distance from the window.



Figure 4.5. Ankrom Moisan office L2 plan with study zones and workstation highlighted.

Results from the study showed a decrease in melanopic illuminance as

distance increased from the window, as would be expected. However, the levels recorded were surprisingly low. The only workstation that exceeded the target value of 240EML in the study was the workstation adjacent to the southeast window on the March 30th study with clear skies. Even with the lights on, only the workstations adjacent to the windows hit or exceeded the 240 EML target, indicating that the electric lights were only providing some supplemental melanopic illuminance. This result was further verified by calculating the melanopic to photopic ratio at each station which typically showed a 10-20% decrease when lights were turned on in the space. Overall, this study indicates that the daylight-driven circadian potential of the office seems limited, likely due to limited access to daylight created by the surrounding buildings.

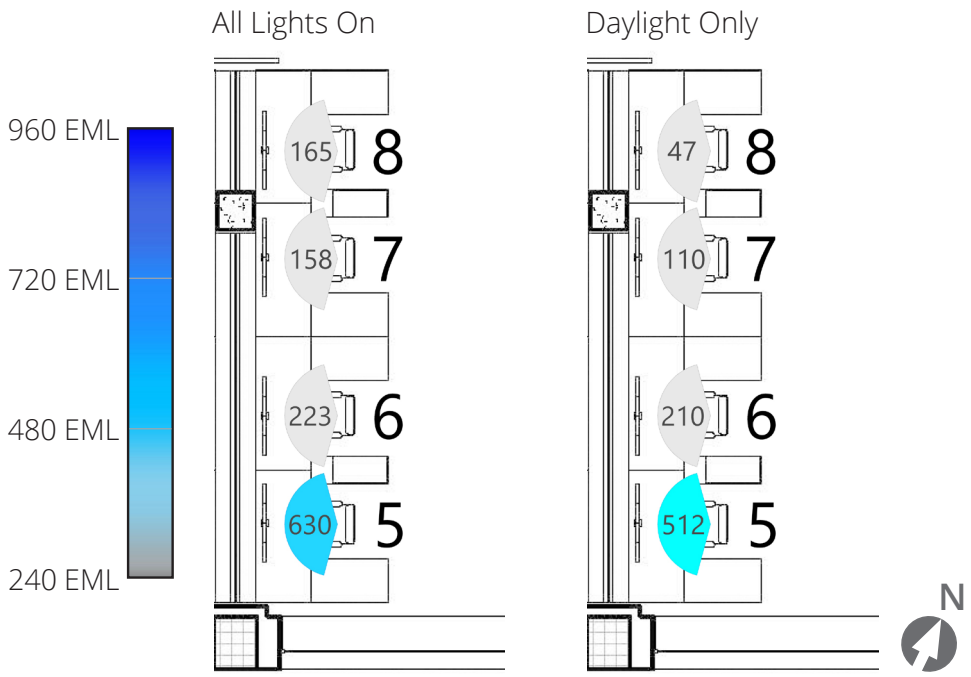


Figure 4.6. Ankrom Moisan, Zone B, March 30th Clear, melanopic illuminance results.

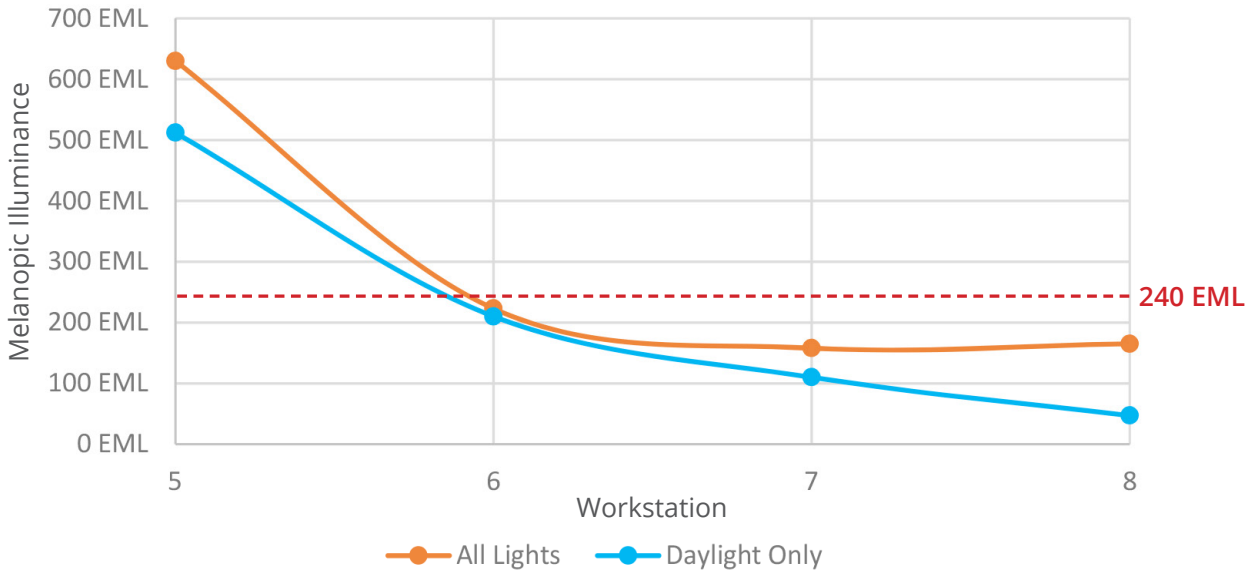


Figure 4.7. Ankrom Moisan, Zone B, March 30th Clear, melanopic illuminance per workstation.

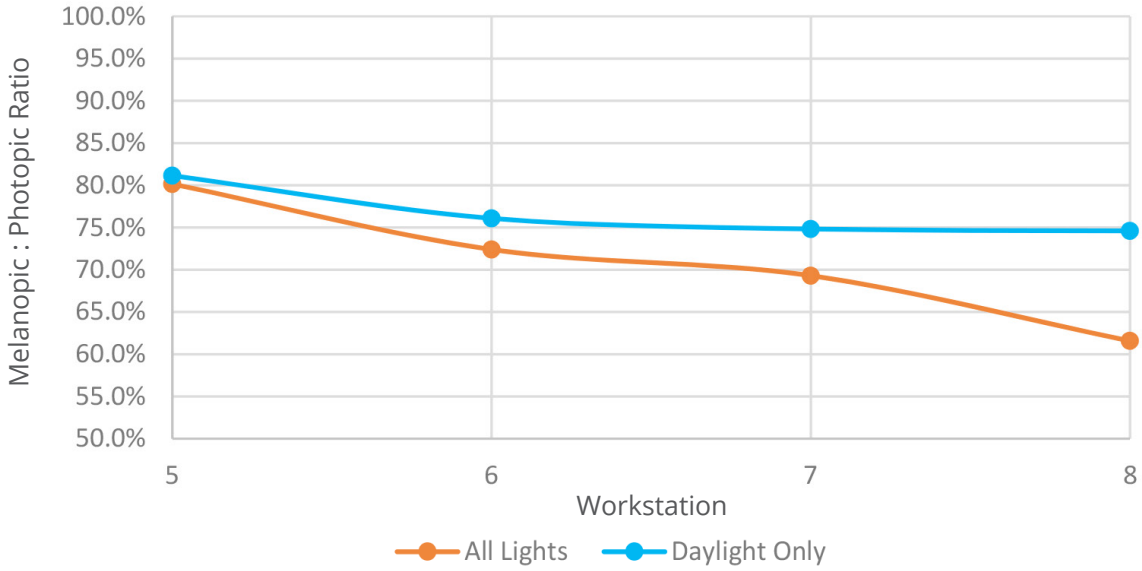


Figure 4.8. Ankrom Moisan, Zone B, March 30th Clear, melanopic photopic ratio per workstation.

4.3. Case Study 2 - Weber Thompson Office

The study of the Weber Thompson office occurred on April 6th in the morning around 10am with partially cloudy skies and a measured global solar irradiance of 241 W/m^2.[26] Due to the varying orientations of workstation throughout the office, workstations selected for study were selected to determine the effect

of orientation of view of the nearest window on circadian potential. Two zone were identified for study, zone A on the west side of the office with punched windows generally and obstructed to views of the sky due to the proximity of the neighboring building, and zone B in the north side of the office with full glazing on both the north and south faces with less sky obstructions.

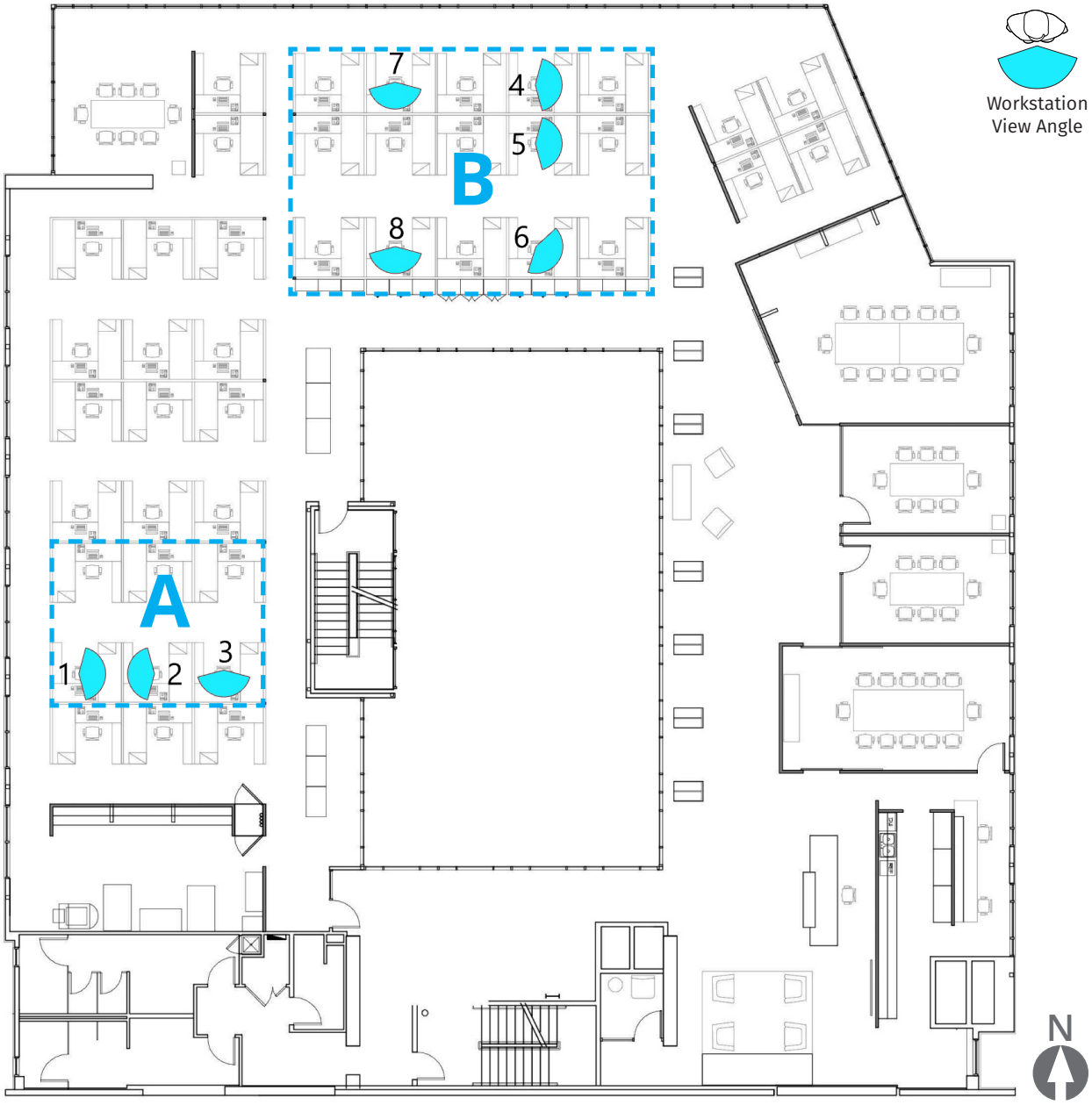


Figure 4.9. Weber Thompson office plan with study zones and workstations highlighted.

The melanopic illuminance measured at workstations in zone A showed expectedly low values, though the station facing the windows to the west of the space showed a significant increase, as compared to views facing away or parallel to the window. Workstations 4-6 in zone B were oriented parallel to the windows and show an increase in melanopic illuminance that correlated to their proximity to the northern windows. This may be due to shading devices and obstructed views to the south, while views to the north were relatively unobstructed. The south facing workstations in zone B, 7 and 8, show an opposite correlation with the northern windows. This may indicate that orientation of the workstation in relation to the nearest window may have a much higher impact on circadian potential than other factors. Overall, this analysis indicates that workstations nearest the windows did receive higher melanopic illuminance, but only if they were oriented to have the nearest window within the frame of view.

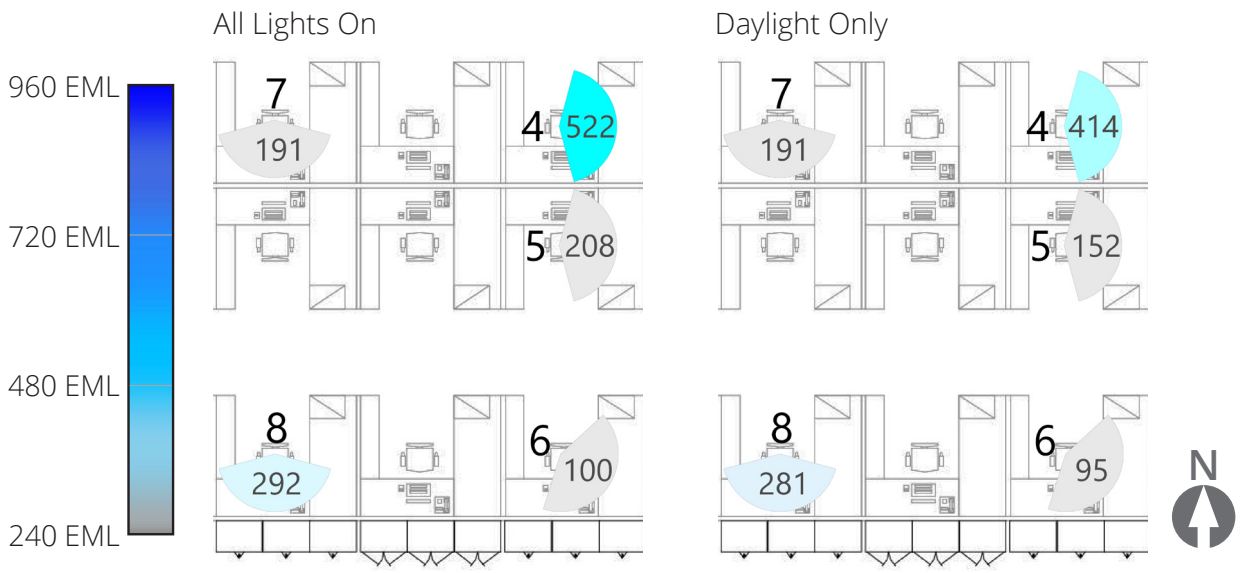


Figure 4.10. Weber Thompson, Zone B, melanopic illuminance results.

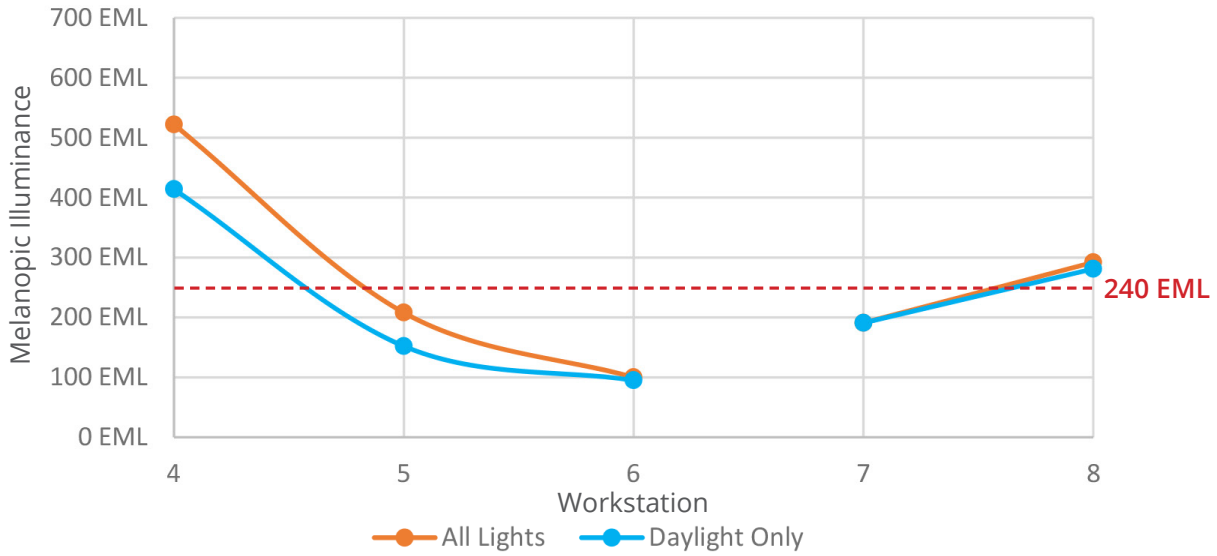


Figure 4.11. Weber Thompson, Zone B, melanopic illuminance per workstation.

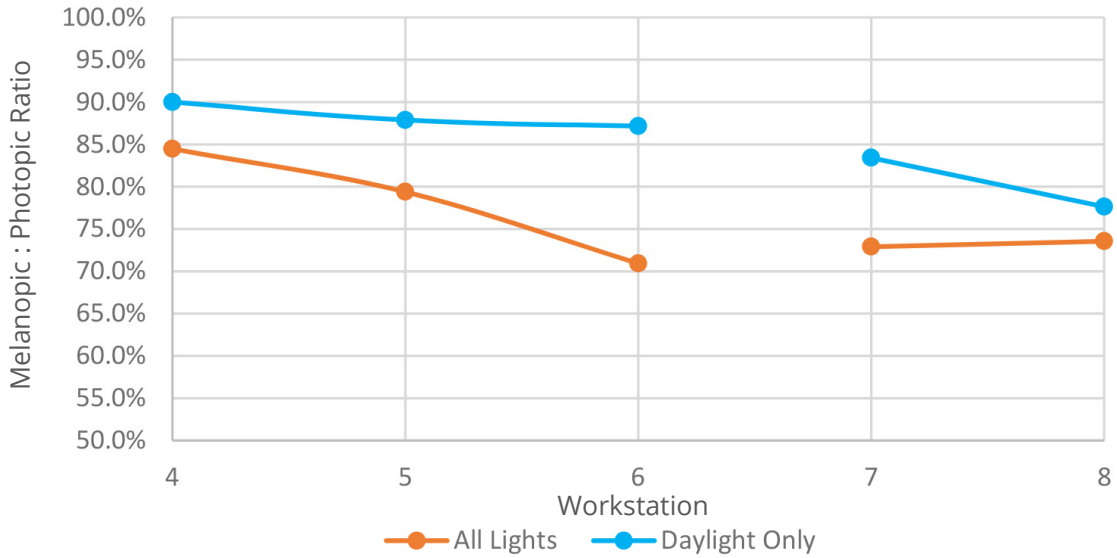


Figure 4.12. Weber Thompson, Zone B, melanopic photopic ratio per workstation.

4.4 Case Study 3 – UW Tower

The study in UW tower of level O-3 was conducted on morning of April 13th around 10am with overcast skies. The measured global horizontal solar irradiance for this study was 87 W/m^2, which, being rather low, did result in low a circadian potential within the office.[26] By the time of the study of level C-1, conducted on the same day in the afternoon around 1pm, the measured

global horizontal solar irradiance had increased to 289 W/m^2. Despite this increase, measured melanopic illuminance values from daylight on this level were considerably lower. This may be due in part to the differences in office layout between the two floors.

Three zones were identified for this study. Zone A towards the center of level O-3 arranged to measure the change in melanopic illuminance with increase proximity to the punched windows on the west wall, zone B on the north side of level O-3 arranged to measure similar effects with the north windows, and zone C on level C-1 arranged to measure these effects with the west windows on that level. While the workstation in this office were oriented as the occupants desired, the workstations selected for study were oriented either towards or away from the window only.



Figure 4.13. UW Tower level O-3 plan with study zones and workstations highlighted.

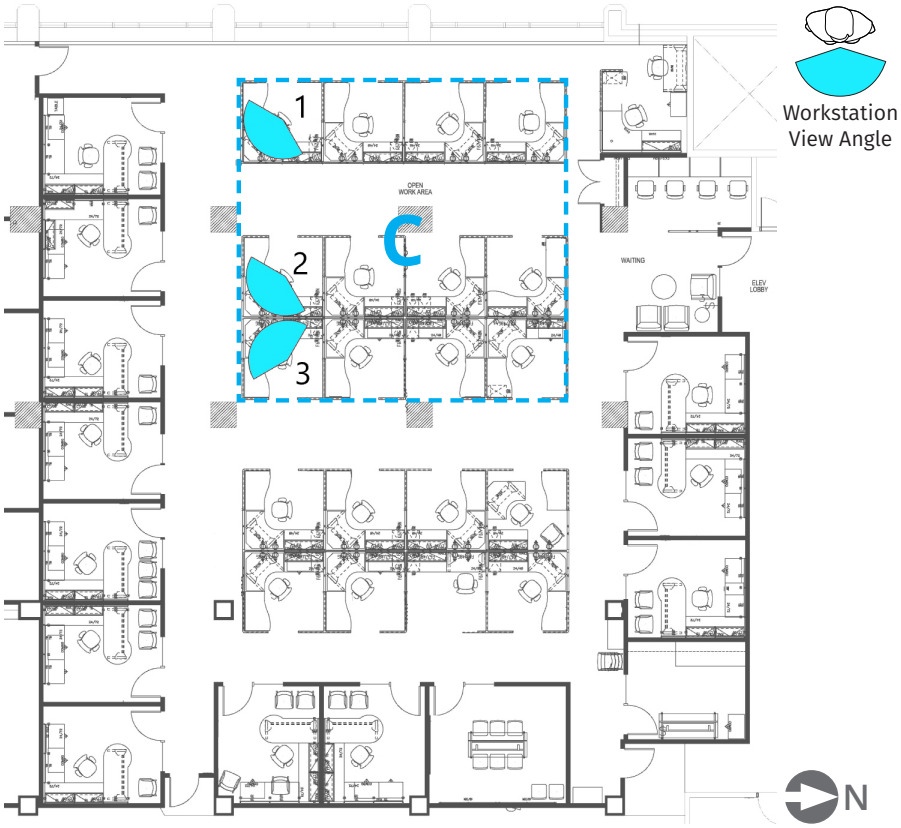


Figure 4.14. UW Tower level C-1 plan with study zone and workstations highlighted.

Unlike case studies 1 and 2, the study of level O-3 was conducted with three HDR images generated for each workstation. The first with all lights active including the task lights set to maximum illuminance and 6500k, the second with all lights active excluding the task lights, and the third with daylight only. This was to measure the maximum effect that the task lights provide as a potentially effective artificial source of circadian stimulus.

Results from this additional study of the task lights revealed a significant increase in melanopic illuminance with the task lights on. 4 of the 12 workstations analyzed on level O-3 (2 of which did not have a task light installed) exceeded the target of 240 EML with the addition of the task light. The common factor for

these stations that exceeded 240 EML was that the task light was positioned in the center of the frame of view. Workstations with the task light located in the periphery of the view of the user did not meet the target.

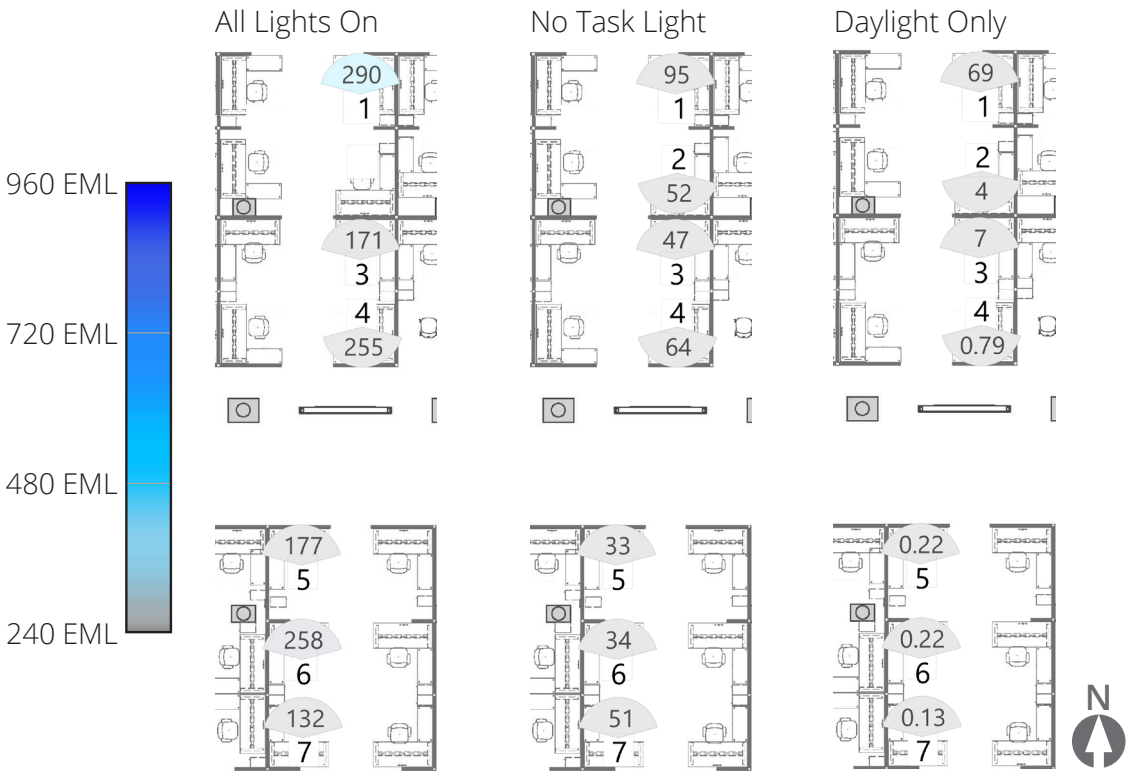


Figure 4.15. UW Tower, level O-3, Zone A, melanopic illuminance results.

Without the task light on, measured melanopic illuminance values were surprisingly low, despite the high color temperature of the troffer lights. This is likely due to the dimming factor applied to the lights. Part of the strategy of the "human-centric" lighting system installed is to reduce energy usage. This is achieved with 3 key strategies: occupancy sensors that turn off the lights shortly after occupants leave the space, daylight sensors with dim the lights near the windows when sufficient daylight is present, and overall dimming of the troffer lights to encourage occupants to use their task lights when

additional illumination is required. With this fact in mind, it is not surprising to find that the measured melanopic illuminance is not very high with the task lights off.

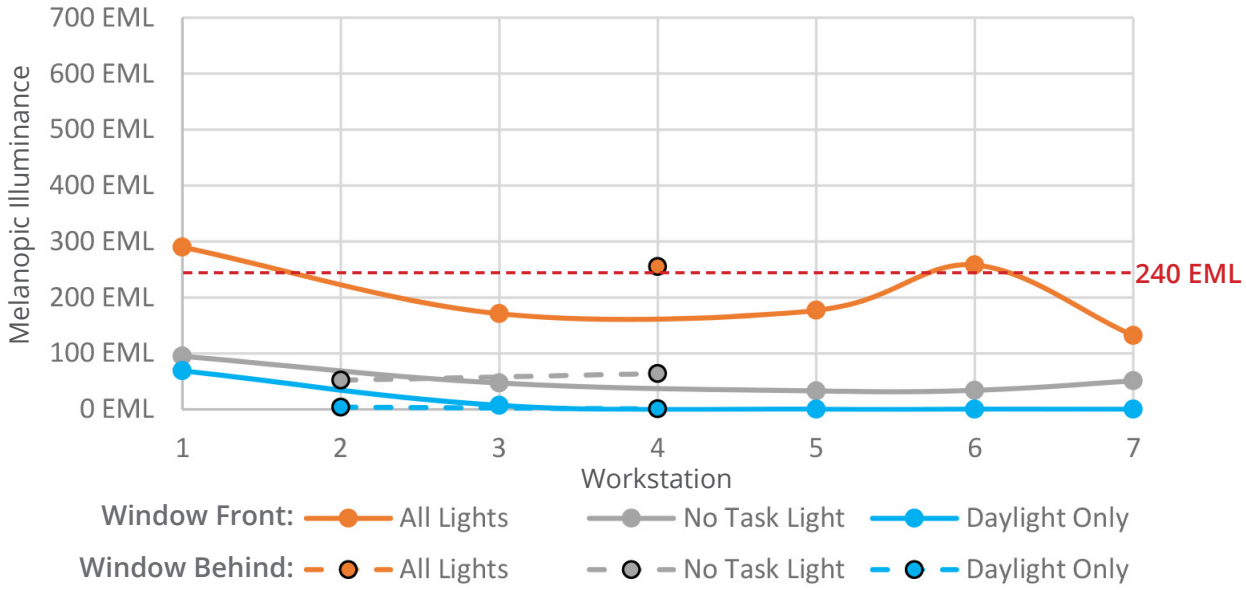


Figure 4.16. UW Tower, level O-3, Zone A, melanopic illuminance per workstation.

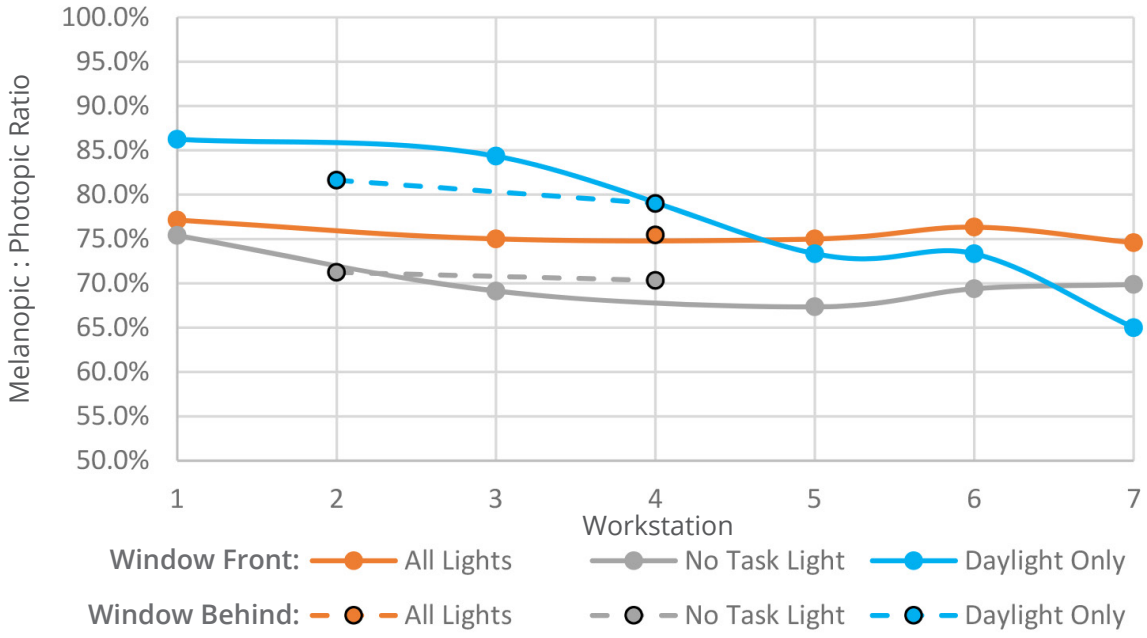


Figure 4.17. UW Tower, level O-3, Zone A, melanopic photopic ratio per workstation.

Measured melanopic illuminance values from daylight alone on level O-3 were very low. Workstation 4 or more stations away from the window received effectively no illuminance from daylight at all. This is likely due in part to the overcast sky conditions, but also is likely due to the deep floor plate. Workstations not receiving any effective daylight were more than 25ft from the nearest window. Additionally, the 54" cubicle dividers created additional obstruction to views of the window within the space.

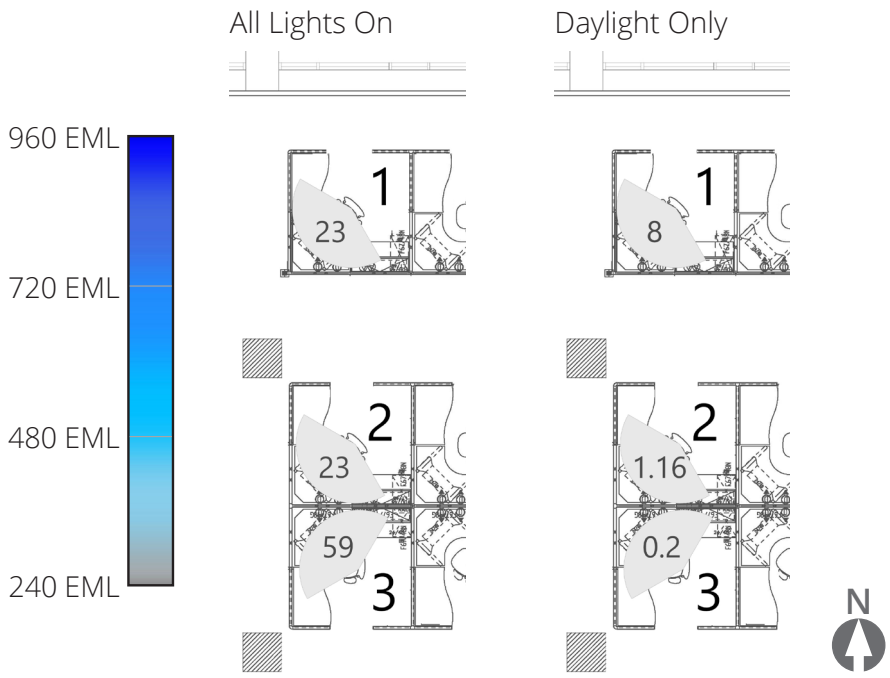


Figure 4.18. UW Tower, level C-1, Zone C, melanopic illuminance results.

The study of level C-1 yielded the lowest measured melanopic illuminance values within the entire set of case studies. The highest measured melanopic illuminance was 59 EML with the lights on. Daylight provided effectively no illuminance within this office with, even for the workstation adjacent to the window. This is likely due to three main factors. One, the florescent troffer

lights were both dim and warm in color (3500k). Two, high 70” cubicle dividers prevent any light from penetrating into the space. Three, workstations near the window were all oriented to face away from the window, reducing any potential for daylight to reach the occupant’s field of view significantly.

4.5. Workplace Lighting Survey Results

Participation in the survey from each office was as well as could be expected with 41 response from Ankrom Moisan, 33 responses from Weber Thompson, and 21 responses from the O-3 level and neighboring C-3 level of UW tower. While responses were not plentiful enough to make statistically accurate findings, the following observations can be made. In order to analyze the results, participants in the Ankrom Moisan and UW Tower surveys were grouped according to their proximity to the nearest window, while participants in the Weber Thompson survey were grouped according to their orientation to the nearest window, as these seemed to be the driving factors for daylight-driven melanopic illuminance in their respective office layouts.

As expected, participants in the Ankrom Moisan and UW Tower studies perceived more daylight and reported more access to views of the sky the closer they were to a window. With some exceptions, participants in these two studies that were seated closest to the window reported being alert through the day more than participants seated further from the windows. In contrast, participants of the Weber Thompson survey that were turned away from the

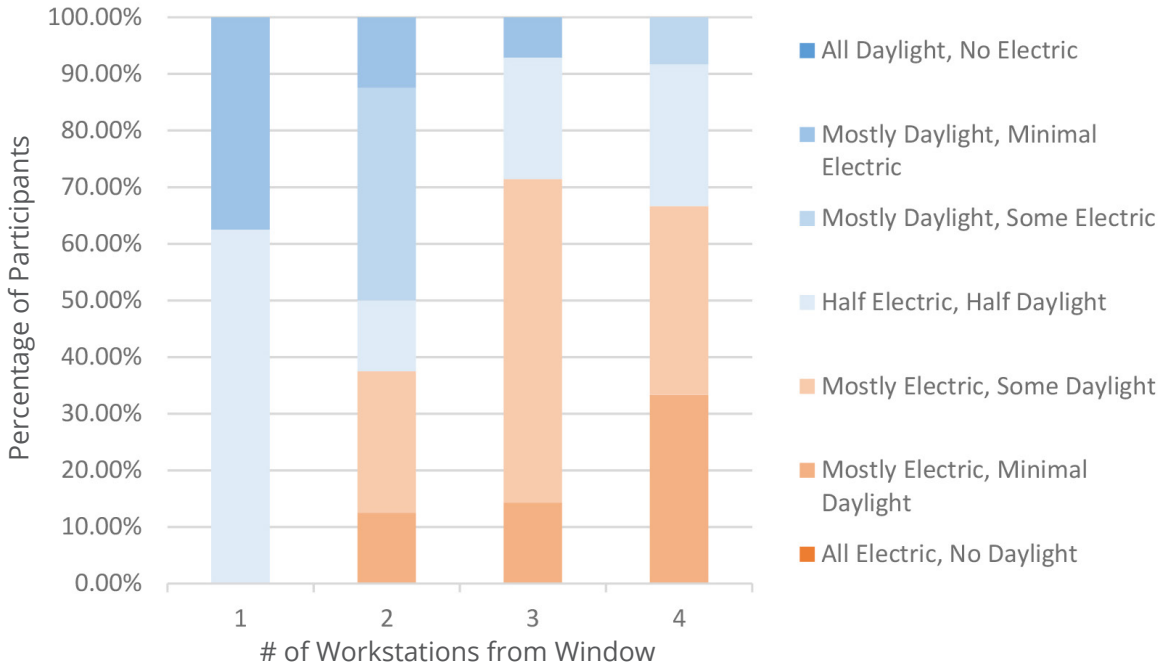


Figure 4.19. Ankrom Moisan workplace lighting survey results, "Is your workstation primarily lit by daylight or electric light?"

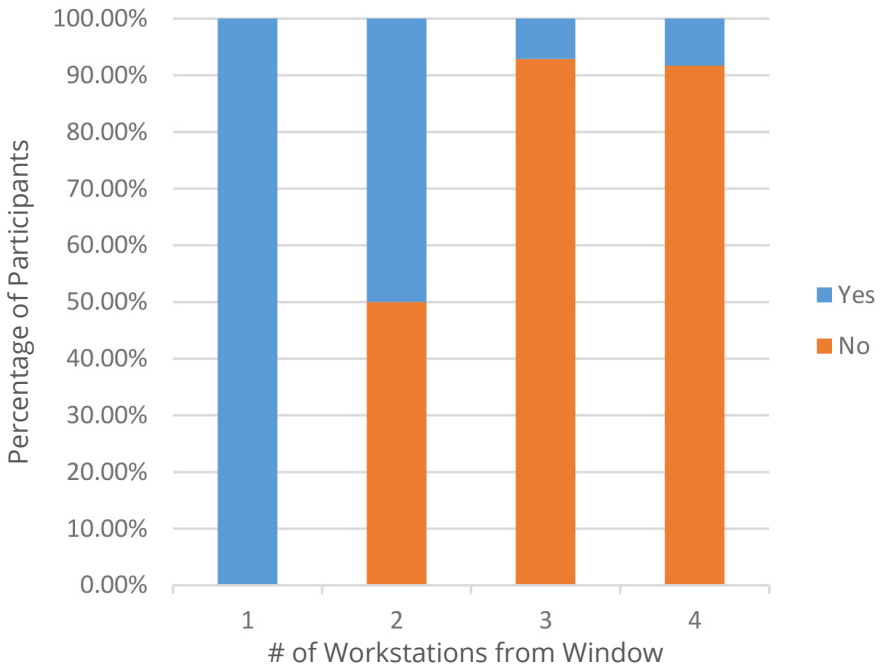


Figure 4.20. Ankrom Moisan workplace lighting survey results, "Can you see the sky while sitting at your workstation?"

nearest window reported more views of the sky and more alertness through the day than other orientations. While this result is counter-intuitive, it is worth noting that due to the narrow floor plates and ample glazing in the Weber Thompson office, occupants with the nearest window behind them would almost always have another window directly in front of them.

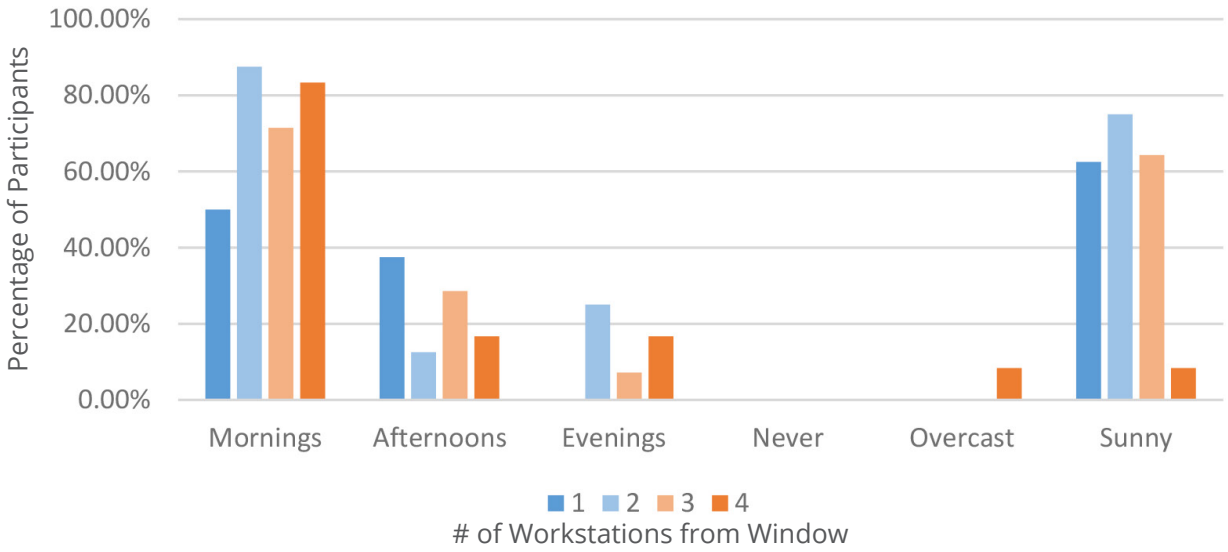


Figure 4.21. Ankrom Moisan workplace lighting survey results, "When do you feel alert while working at your workstation?"

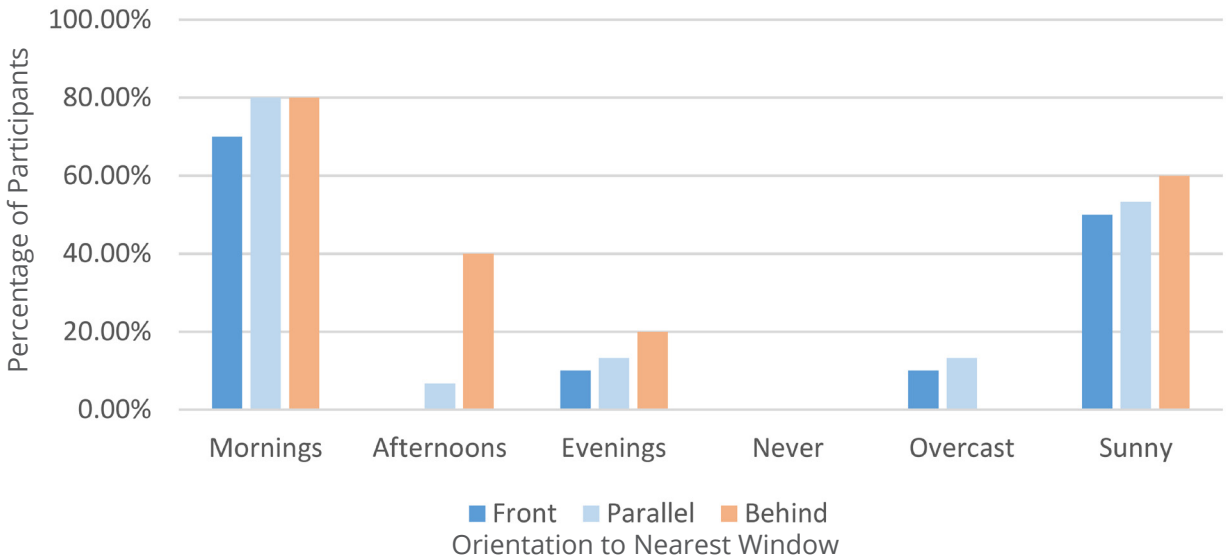


Figure 4.22. Ankrom Moisan workplace lighting survey results, "When do you feel alert while working at your workstation?"

4.6. Case Study Conclusions

The conclusion of these case studies revealed a variety of factors that related to the current status of circadian lighting in these offices today. Daylight was the primary contributor to melanopic illuminance in all three offices with the exception of the customizable task lights. Only workstation nearest the source of daylight met or exceeded the WELL building standard target melanopic illuminance of 240 EML with daylight alone.

Architectural parameters that lead to variances in measured melanopic illuminance in these case studies reveal potential avenues for improvement to better utilize daylight in these spaces for circadian stimulus. These parameters included:

- **Seating orientation relative to the nearest window.**
- **Orientation of the nearest window to the sun.**
- **Proximity to the nearest window.**
- **Shading devices and other obstructions to views of the sky.**
- **Materials present within the frame of view.**

Further validation of the relevance of these architectural parameters was given by the results of the workplace lighting survey in which participants that reported being alert later into the day also reported greater access to views of the sky and more perceived daylight. These findings helped to shape the next step of this analysis of daylight-driven circadian lighting design by defining some factors for further study through simulation.

5. Circadian Lighting Simulations

While field measurements of daylight-driven circadian lighting can yield valuable data for analysis, it comes with many limitations. When analyzing existing spaces, it is difficult to control variables that may affect the results of the field measurements. This includes materials within the study area, access to the space if it is in regular use, current state of maintenance of lighting and shading mechanisms, and most of all, the passing of time as data is collected. Capturing all the exposures required to generate a single HDR image for analysis took 60-90 seconds. During this time, daylight conditions can change due to the changing position of the sun, and inconsistent cloud cover and density. If this occurs during the image capture process, it can result in inaccurate measurements. If it occurs over the period required to capture all of the HDR images in the space for comparative analysis, which is almost inevitable, it can cause variances in the data that can alter the final results. Lastly, even if all of the other variable can be accounted for, the time required to collect enough data for an analysis of the daylight-driven circadian lighting in a space over a wide range solar conditions can be very prohibitive. By accurately simulating a space for analysis, these limitations can be overcome to the extent of the capabilities of the software.

The daylight-driven circadian lighting simulations were completed in 3 phases: A simulation validation study to verify the validity of the simulation results, a

control study of a simplified hypothetical office model to compare results to, and a series of studies isolating various architectural parameters to determine their effect on the circadian potential of the space. Circadian potential in this case is defined as the maximum percentage area in a given space that daylight provides 240 EML or more in an idealized environment. The architectural parameters selected for further analysis in this study were: Window head height, building orientation, shading devices, visual obstructions to the sky, room depth, and a cursory analysis of the effectiveness of skylights.

The data from these simulations was analyzed using three different metrics. First was through the use of visualizations that display the data collected across the entire grid of sensors in the space allowing for visual interpretation and comparison of the simulation results. Second was by charting the average measured melanopic illuminance values across the depth of the space. These averages were generated by combining the average values from the summer solstice, the winter solstice, the fall equinox, and a duplicate data set of the fall equinox to approximate the data from the spring equinox. This method creates an approximation of the annual circadian potential of the space that, while not accurate to the full range of annual climate conditions for the area, is sufficient for the comparative analysis in this study. The third metrics consisted of calculating the percentage sensors in a given view direction within the space that met or exceeded the target melanopic illuminance value from the

WELL standard of 240 EML. The combined use of these three metrics allowed for a comprehensive analysis of the simulated data that lead to the creation of some potential daylight-driven circadian lighting guidelines.

5.1. Simulation Validation Study

To validate the accuracy of the simulations generated in ALFA, it was necessary to create simulations based upon one of the case studies so as to compare the simulated data to the field measurements. For this study, a model of the Ankrom Moisan office was imported into Rhino from an original Revit model of the office created by Ankrom Moisan for their tenant improvements project in 2016. Extraneous data unnecessary for the lighting simulation was removed from the model and approximate materials selected from the ALFA library to represent materials observed in the existing office. As these simulations were specifically generated to measure daylight only, no electric lighting was retained in the model. A simplified massing model of the downtown Seattle context was generated based upon GIS shape files.

For this validation study, both the March 30th study and the April 14th study from the Ankrom Moisan case study were simulated. To match the parameters of the field measurements as closely as possible, it was necessary to generate a view sensor that matched the approximate position, height, and view orientation of the camera for each workstation analyzed in the case study. Each workstation measurement was simulated individually at the exact time and

date of the individual measurements from the case study. Skies generated for the simulation were selected from four options in ALFA (clear, hazy, overcast, and heavy overcast) to best fit the observed sky conditions from the study.

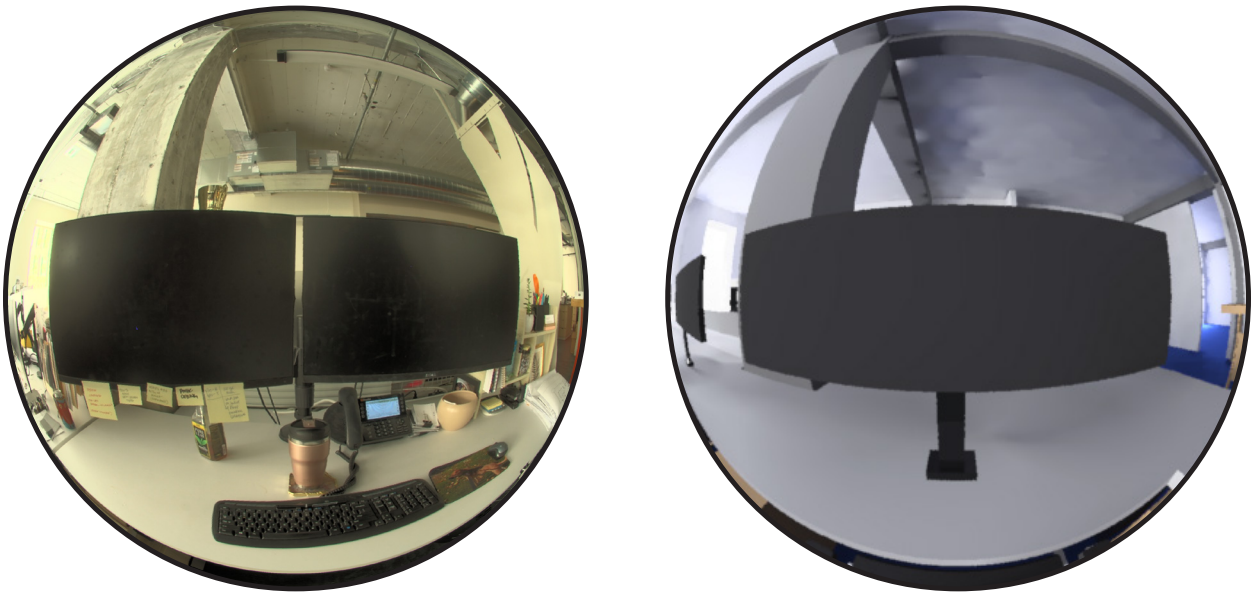


Figure 5.1. Comparison of an HDR fisheye from the Ankrom Moisan case study (right) to a fisheye visualization from the Ankrom Moisan office simulation (left).

The final results from the simulations revealed measured values that were within an acceptable margin of error for the purposes of this study. For the March 30th and April 14th studies the melanopic illuminance values had a standard deviation from the field measurements of 36.4 EML and 26.3 EML respectively, the photopic illuminance values had a standard deviation of 59.6 lux and 23.6 lux respectively, and the melanopic to photopic ratios had a standard deviation of 16.7% an 14.4% respectively. Potential sources for the error in the simulation measurements include approximate material selection, additional materials present in the scene that were not simulated, and most significantly, the limited selection of sky conditions in ALFA.

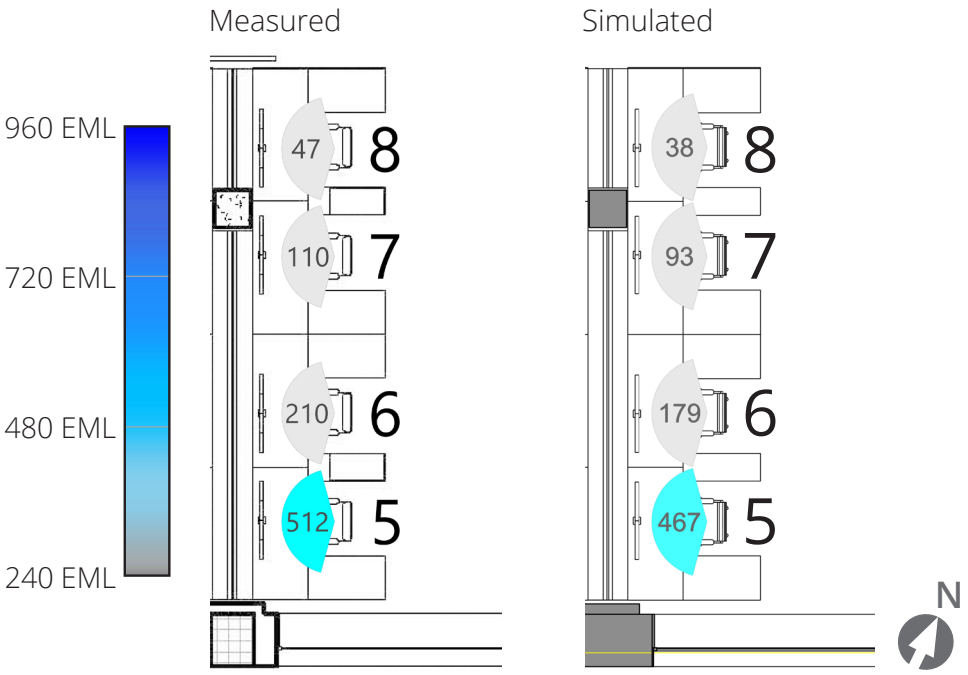


Figure 5.2. Ankrom Moisan, Zone B, March 30th Clear, measured versus simulated melanopic illuminance results

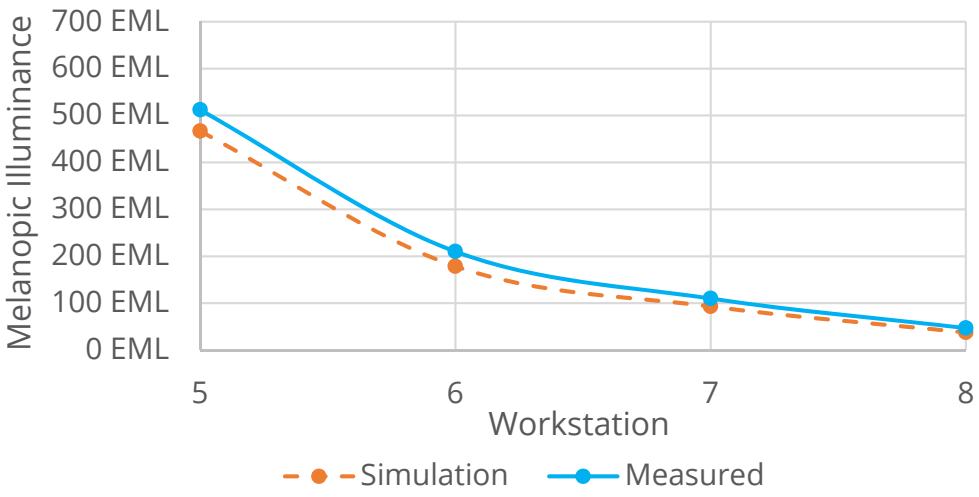


Figure 5.3. Ankrom Moisan, Zone B, March 30th Clear, measured versus simulated melanopic illuminance per workstation

5.2. Control Study

To isolate the effects of the architectural parameters selected for further study, a simplified hypothetical office model was constructed in Rhino. This model consisted of a rectangular space with a width of 40'-0", a depth of 70'-0", and

a ceiling height of 10’-0”. Four windows with a sill height of 3’-0” and a head height of 8’-0” were placed in the south wall of the space, which had a wall thickness of 0’-9”. Initial simulations of the hypothetical office model were completed with a room depth of 40’-0”, however, these simulations yielded results that did not capture the full gradient of melanopic illuminance within the space. Due to these results, the room depth was increased to 70’-0”.

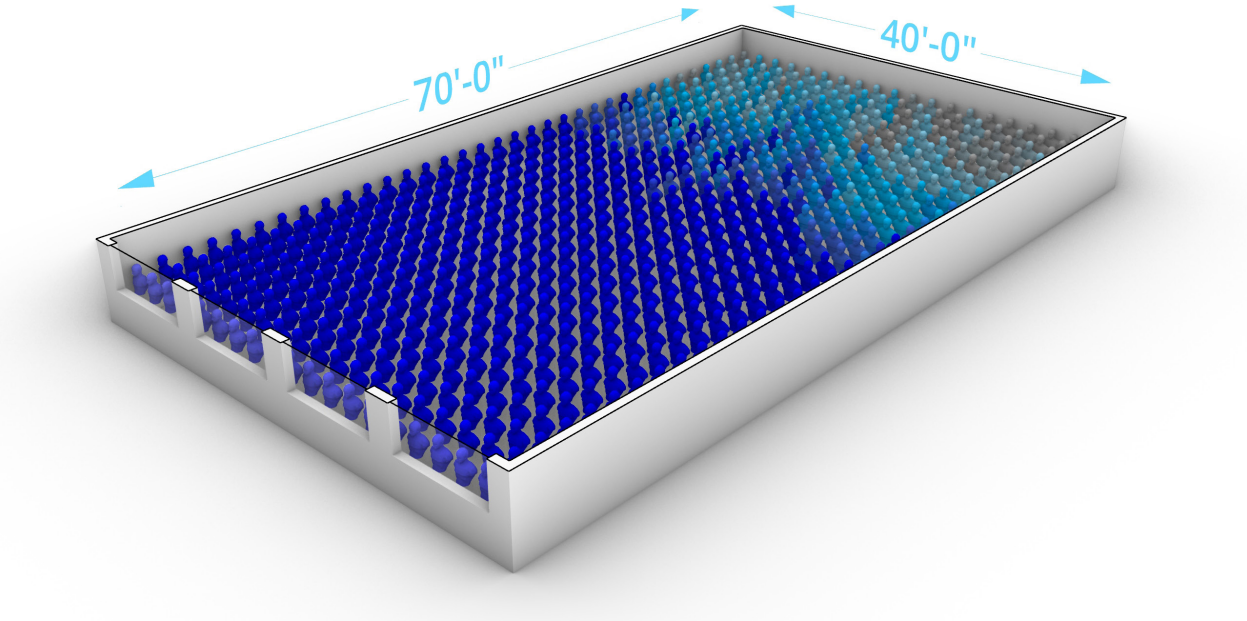


Figure 5.4. Hypothetical office control model axon

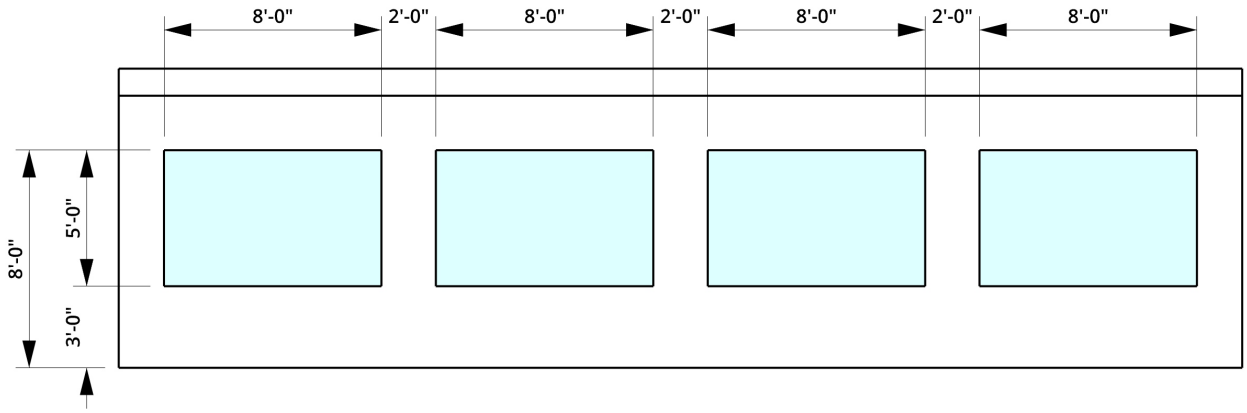


Figure 5.5. Hypothetical office control model elevation

This control study yielded some initial findings on effects of the sky conditions selected for simulation, and the orientation of view within the space on circadian potential. As expected, the sky conditions had a significant impact on circadian potential of the space. The June 21st simulation with clear skies resulted in a depth of penetration reaching 70ft to the back of the room for sensors facing the window with an average of 240 EML or more, and over 98% of sensors meeting or exceeding 240 EML overall, while the December21st simulation with overcast skies resulted in only depth of penetration of only 28ft, and only 40% of sensor meeting or exceeding the target. This equates to a 59% reduction in the circadian potential of the space that can occur due to the condition of the sky.

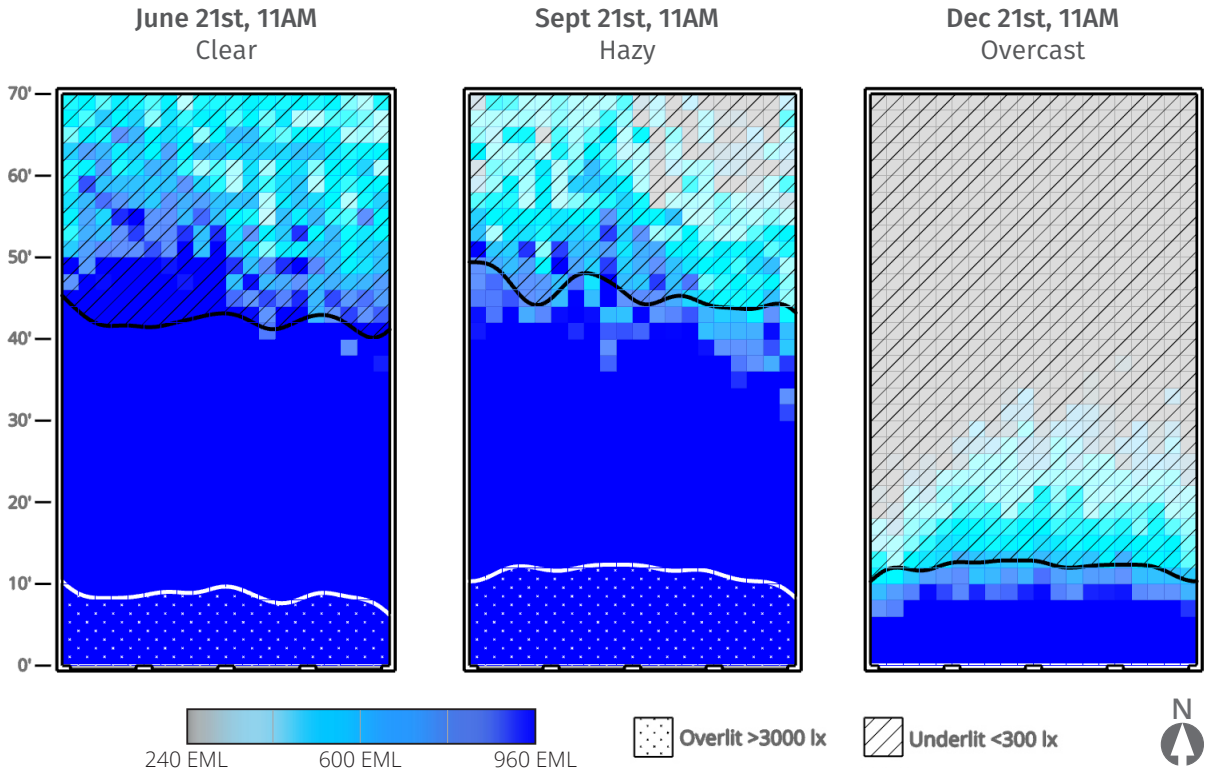


Figure 5.6. Control study, sky condition sensor grid visualizations.

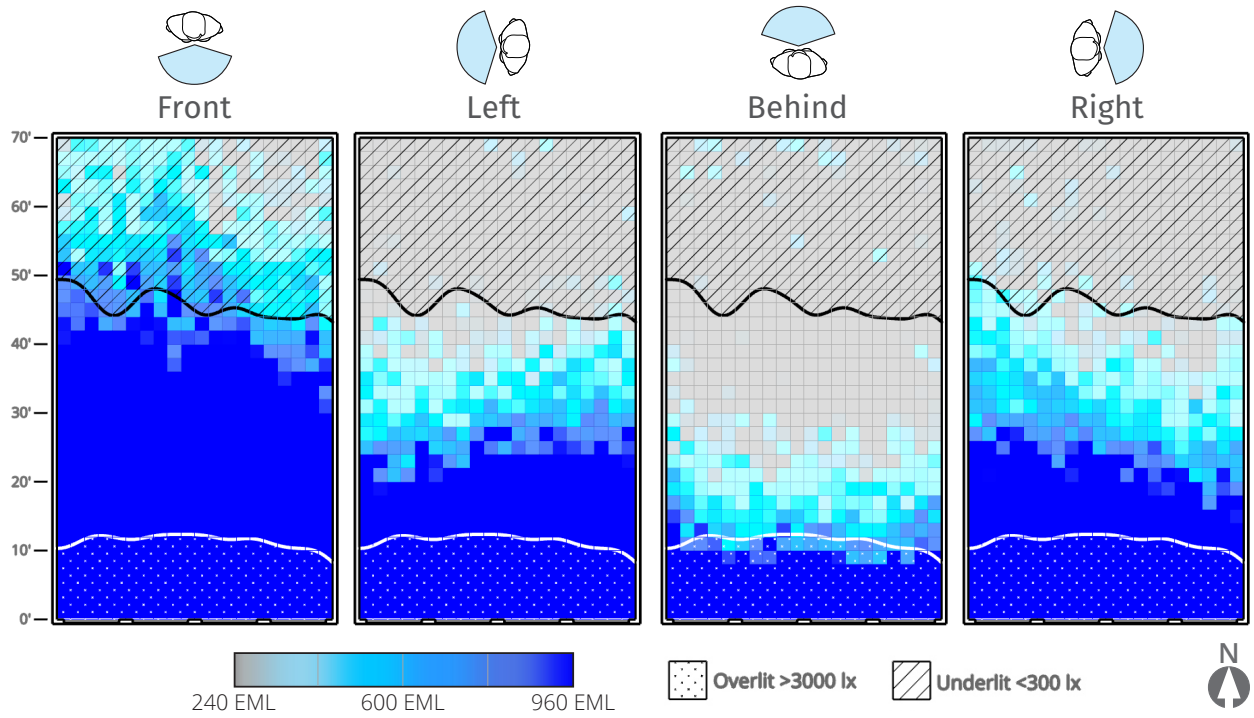


Figure 5.7. Control study, view orientation sensor grid visualizations, September 21st, 11am

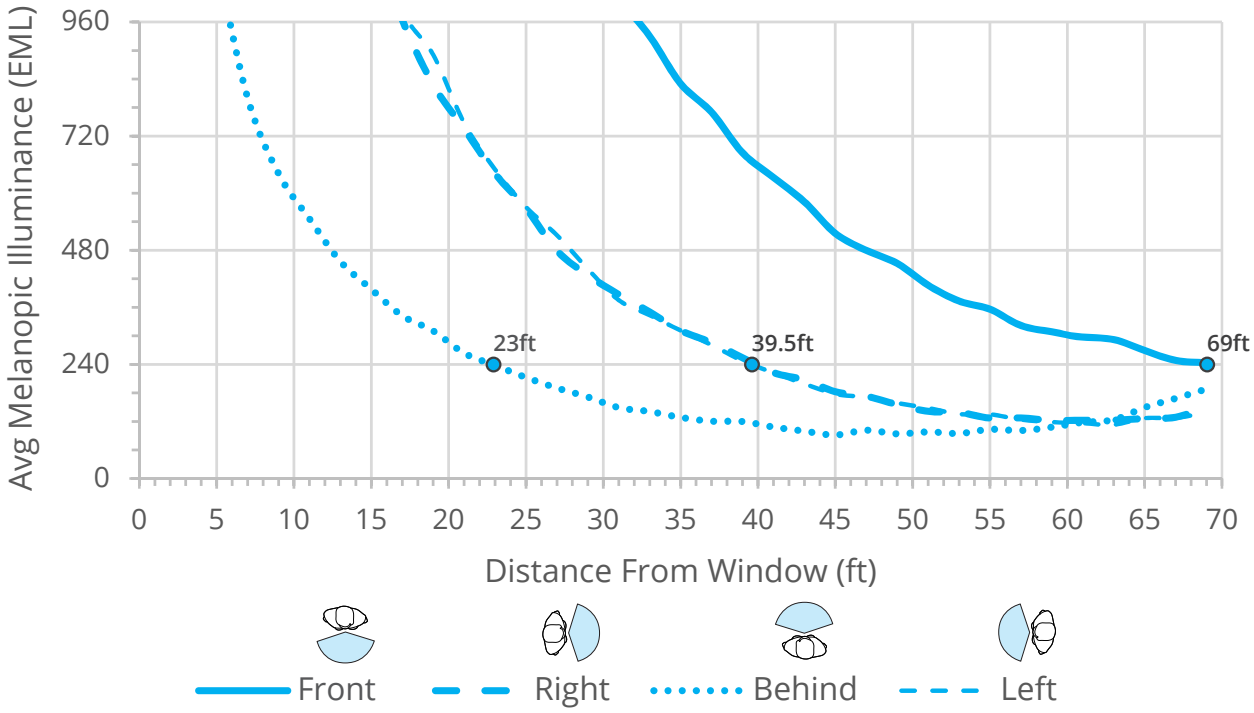


Figure 5.8. Control study view orientation, depth of penetration.

The orientation of view within the space also had a significant impact on circadian potential. The depth of penetration for sensors facing towards, parallel, and away from the window was 69ft, 39.5ft, and 23ft respectively. The percentage of sensors meeting or exceeding 240 EML was 84%, 57%, and 35% respectively. This equates to up to a 58% change in the circadian potential of the space due to the orientation of view alone. These results also indicate a strong correlation between the ideal orientation of occupants to maximize circadian potential and the distance of the occupants from the window.

5.3. Window Head Height

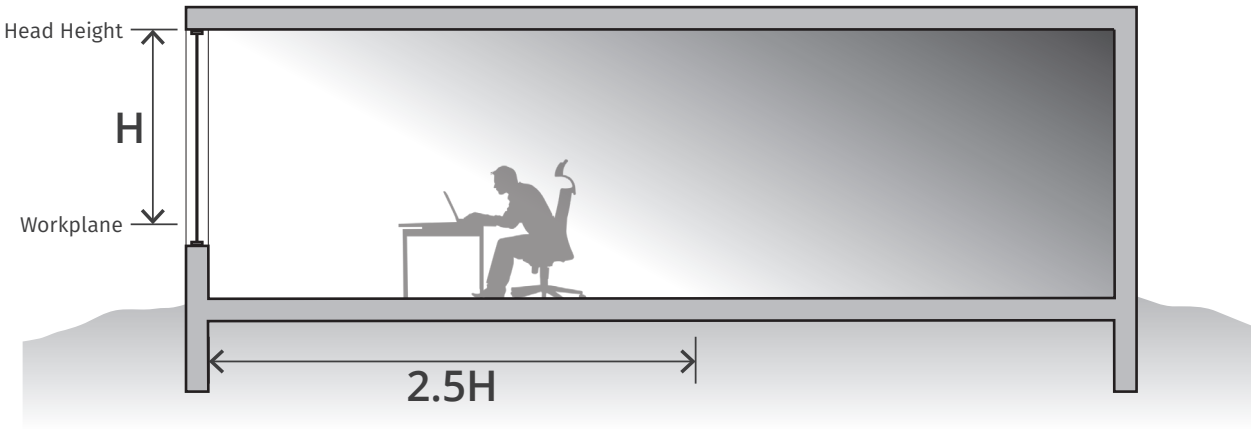


Figure 5.9. The 2.5H guideline

The 2.5H guideline is a common rule-of-thumb in daylighting design which states that “sufficient daylight for the desk plane will be delivered at a depth of 2.5 times the height of the window above the desk plane”. This study was completed to determine if there is a similar linear relationship between the head height of the window and the circadian potential of a space. To test this, simulations of the hypothetical office with the head height of the window

altered to 7’-0” and 9’-0” above floor finish (AFF). As the sill height of the window remained static, the window to wall ratio (WWR) also changed to 0.32 and 0.48 respectively. Along with the data from the control study, which had a window head height of 8’-0” AFF and a WWR of 0.40, this yielded results that showed an increased depth of penetration of 8.5ft, 5ft, and 3ft per foot of added head height AFF for sensors facing towards, parallel, and away from the window respectively.

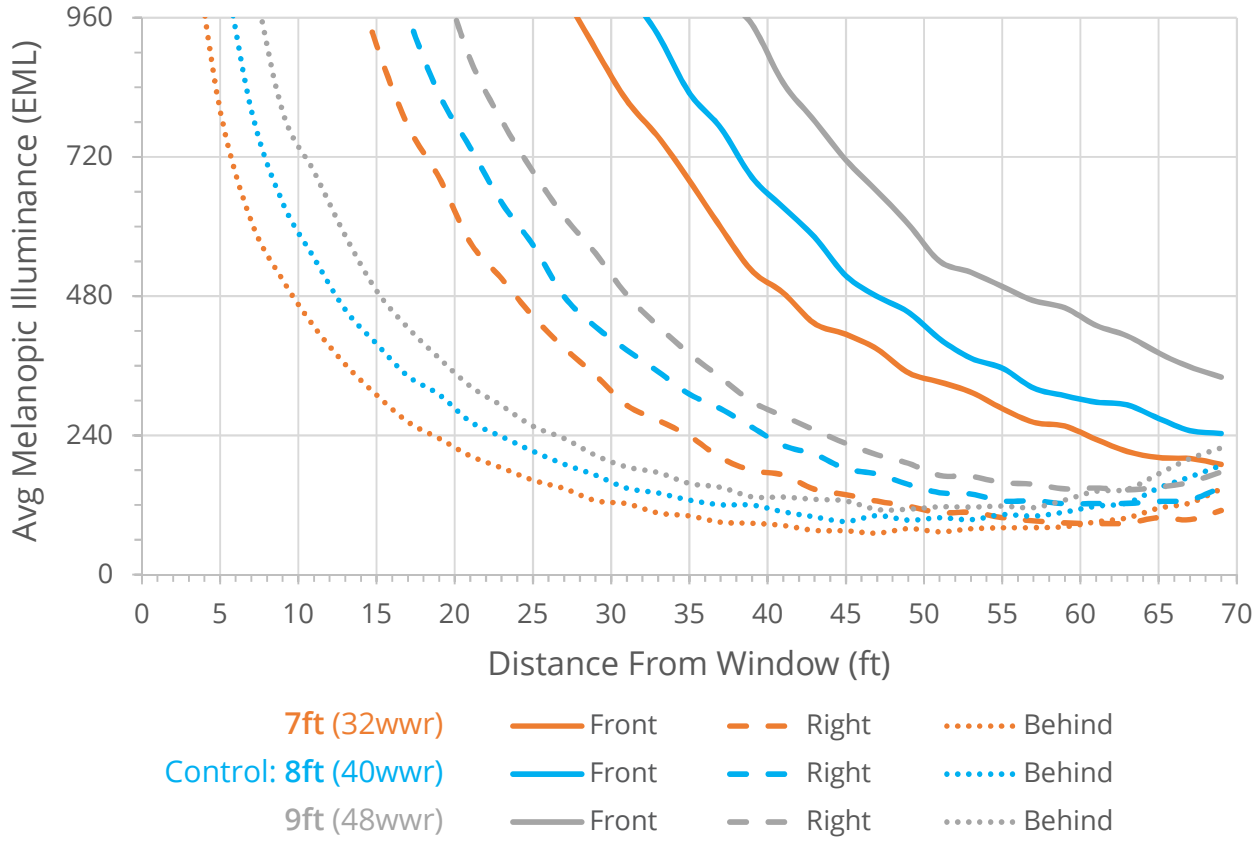


Figure 5.10. Window head height, depth of penetration

For the 2.5H guideline, the value “H” is defined as the head height of the window above the desk plane. Measuring the head height in this way for the three models results in H values of 4.5, 5.5, and 6.5. Comparing these values to

the depth of penetration for sensor that met or exceeded 240 EML resulted in a linear correlation of 12H, 7H, and 4H for sensors facing towards, parallel, and away from the window respectively.

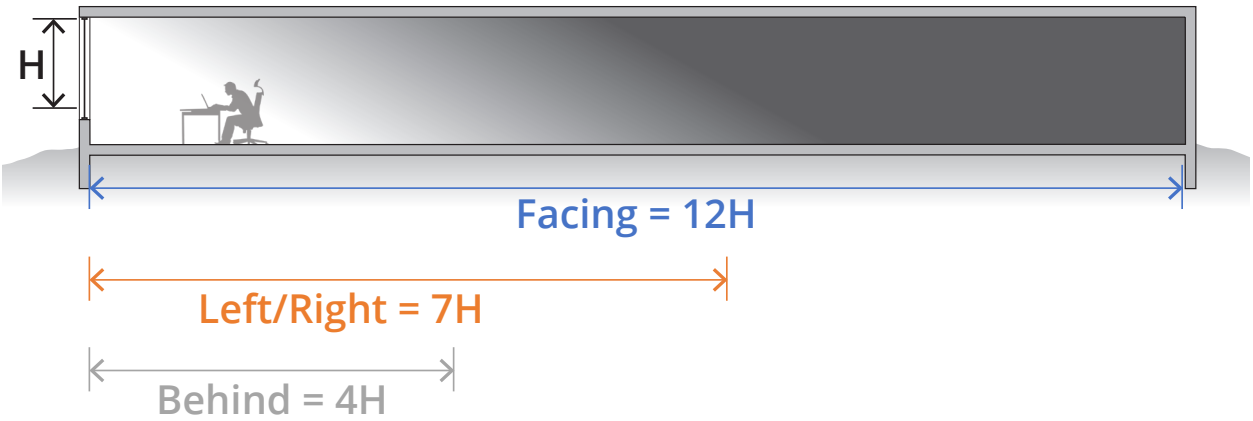


Figure 5.11. Melanopic version of the 2.5H rule

Despite this linear correlation found in this study between the head height of the window and the depth of penetration for circadian stimulus, the data from this finding indicates that the effect is minimal in comparison to other factors that can override it significantly. Additionally, due to the structuring of this study, the correlation determined here can also be attributed to the change in window wall ratio between each model. Additional study will be required to isolate the effect of altering the head height of the window without altering the window wall ratio.

5.4. Building Orientation

To analyze the effects of the orientation of the building on circadian potential, the control model was rotated in 90 degree increments to orient the windows to the east, north, and west. The results from these simulations revealed that

the north orientation decreased the depth of penetration to 48ft for sensors facing towards the window, a 28% reduction, and a 23% decrease in the circadian potential, as compared to the control study with a south orientation. The variance between the east, west, and north orientations was only 6 ft of penetration and 7% of circadian potential. This result indicates that views to the sky are the primary source of circadian stimulus, while access to direct sunlight only boosts the circadian potential by 23%.

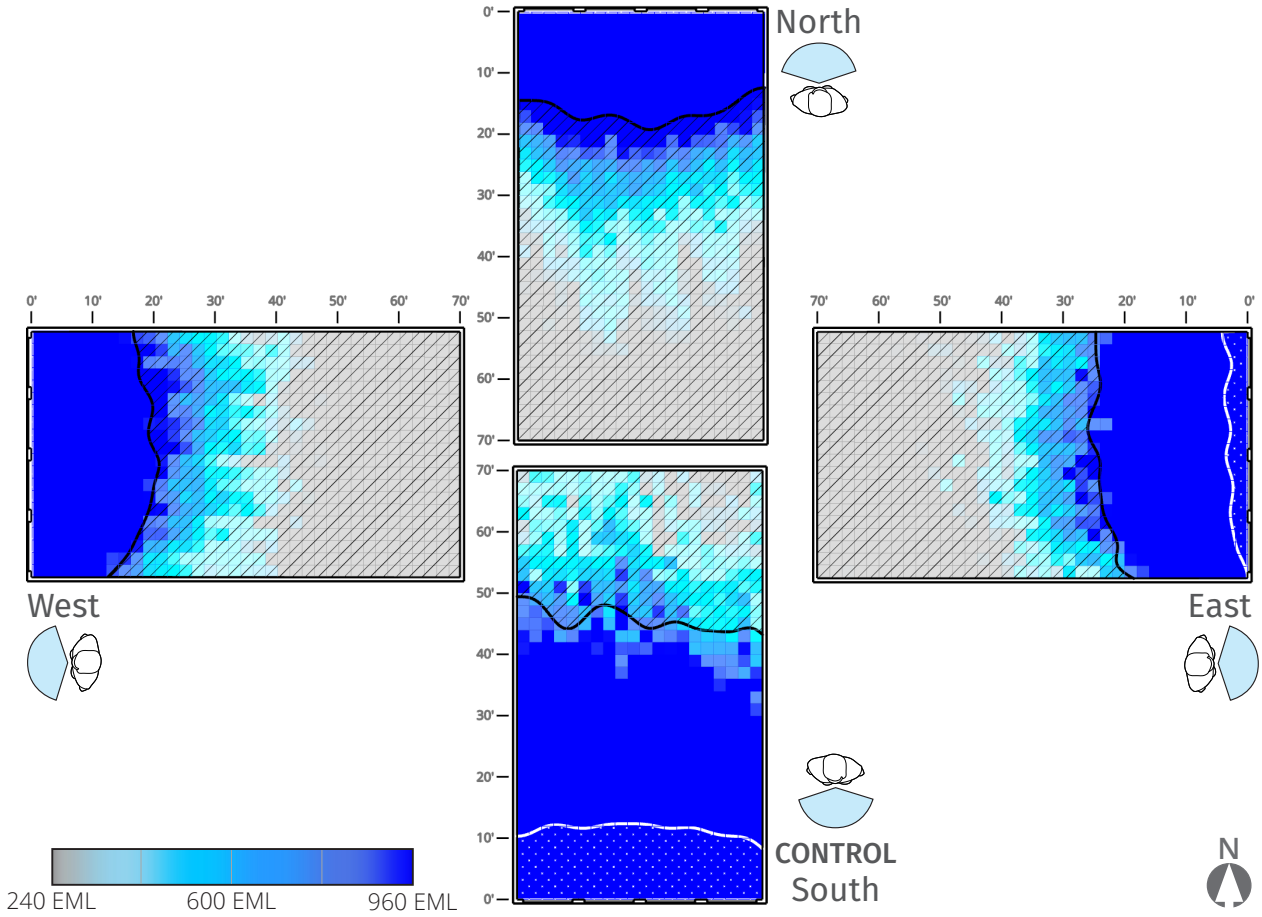


Figure 5.12. Building orientation sensor grid visualizations, September 21st, 11am, facing towards the window

5.5. Shading Devices

Four shading devices were tested in this study: a simple awning designed to block the summer sun between March 21st and September 21st, horizontal blinds designed to block the summer sun as well, and electrochromic glass set to 18% and 6% transmittance. Results from the simulation of the awning and horizontal blinds showed a minimal effect on the circadian potential of the space as compared to the control, with reduced depth of penetration of only 5ft and 1ft, and a reduction of 6% and 2% in circadian potential respectively, for sensors facing towards the window. This result is likely due to these shading devices not serving as a significant impediment to views of the sky.

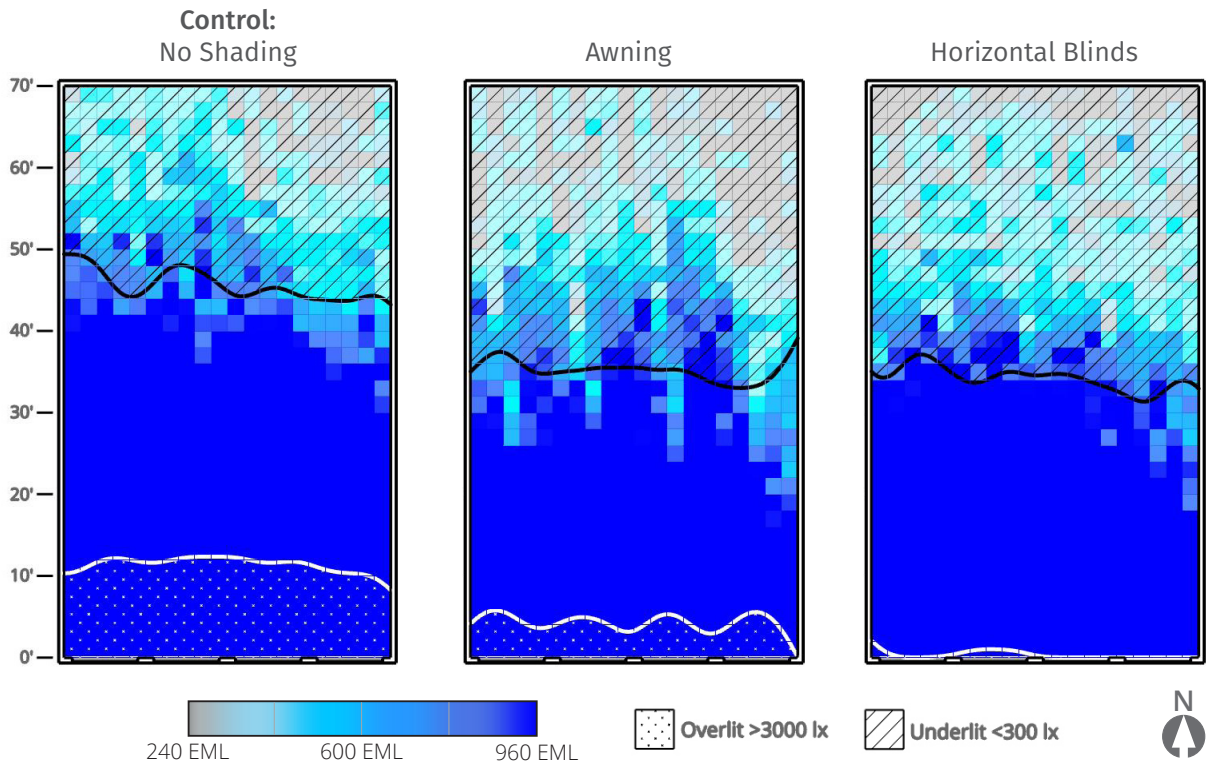


Figure 5.13. Shading devices, awning and horizontal blinds sensor grid visualizations, September 21st, 11am, facing towards the window

In contrast, the electrochromic glass had a very significant impact on circadian potential. The electrochromic glass set to 18% light transmittance resulted in a depth of penetration of only 25ft, and the circadian potential of only 35%, over a 58% reduction as compared to the control without shading for sensors facing towards the window. Decreasing the light transmittance of the electrochromic glass to 6% resulted in minimal circadian potential in the space with depth of penetration of only 11ft and a circadian potential of only 17% for sensors facing towards the window. This result illustrates that shading devices which significantly alter the intensity and/or color of the daylight coming through the window have a very adverse effect on circadian potential.

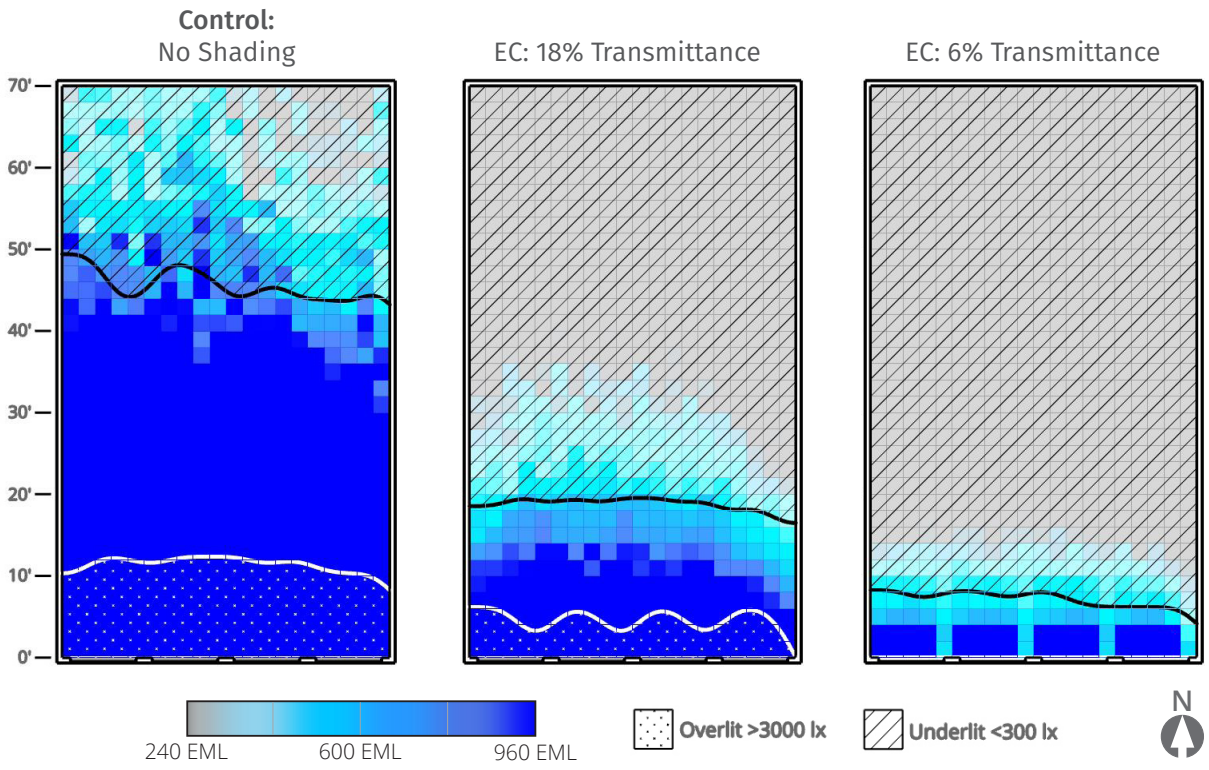


Figure 5.14. Shading devices, electrochromic glass sensor grid visualizations, September 21st, 11am, facing towards the window

5.6. Visual Obstructions of the Sky

For this study, the hypothetical office model was set into the downtown Seattle context generated for the Ankrom Moisan model used for the simulation validation study. The context model was then rotated to have an orthogonal relationship to north in order to have a directly comparable results to the control study. The obstructed views of the sky created by the surrounding buildings resulted in a depth of penetration of only 28ft and a reduction in circadian potential of over 53% for sensors facing towards the window. This suggests the context and visual obstruction to the sky can have a significant impact on the circadian potential of a space. Further study will be required to determine the exact correlation between the percentage obstruction of view to the sky and circadian potential.

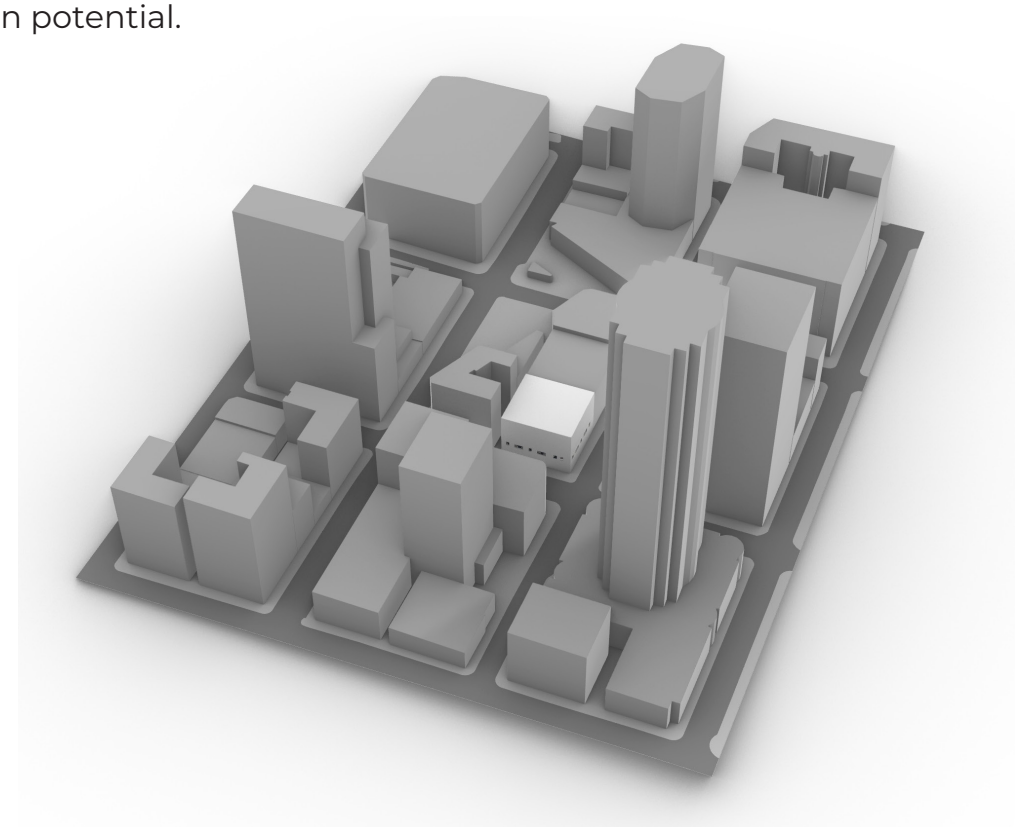


Figure 5.15. Downtown Seattle context model

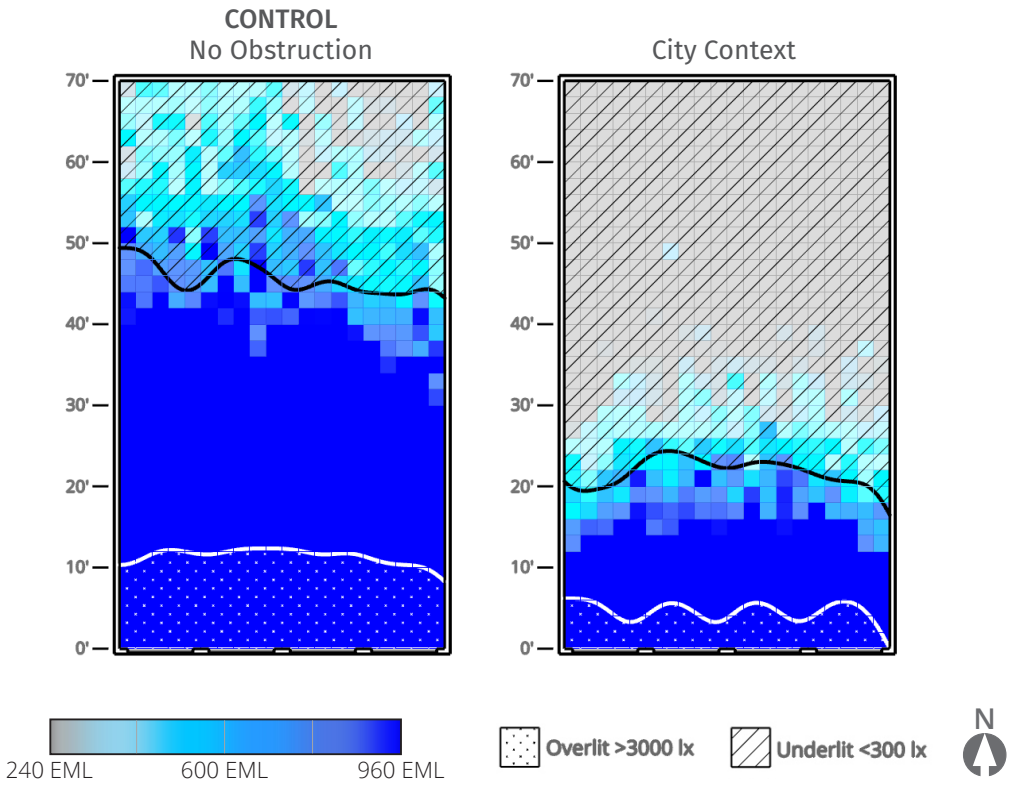


Figure 5.16. Visual obstructions sensor grid visualizations, September 21st, 11am, facing towards the window

5.7. Room Depth

As the room depth of the models for this study was increased to observe the full gradient of melanopic illuminance in the space, it was necessary to quantify how this variable could also change the circadian potential of the space. Reducing the depth to 34ft resulted in a compression of the daylight in the model through inter-reflections. While the circadian potential increased overall in this model as compared to the control, the largest impact observed due to the reduction of room depth was for sensors facing away from the window, which received over a 129% increase in circadian potential. This result indicates that, as with typical daylighting practice, reducing the depth of the room can also significantly increase circadian potential through inter-reflections.

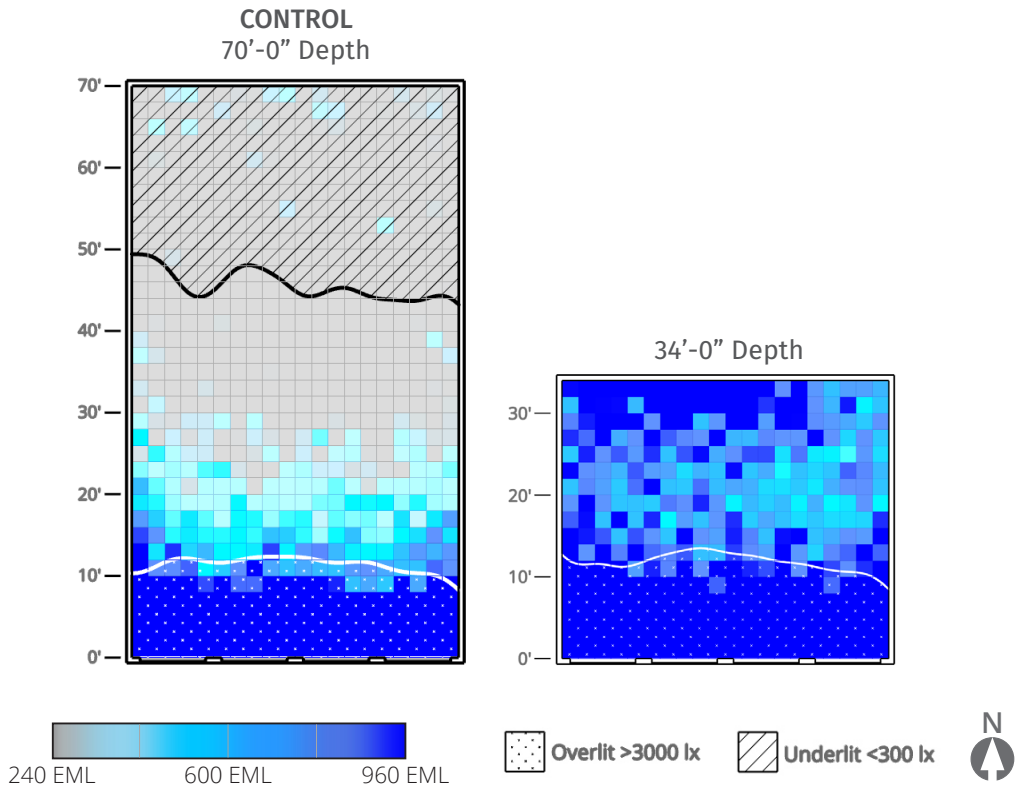


Figure 5.17. Room depth sensor grid visualizations, September 21st, 11am, facing away from the window

5.8. Skylight Effectiveness

To test the effect of skylights on circadian potential, a new hypothetical office model was generated with width and depth of 50'-0" and a ceiling height of 10'-0". One 6' x 6' square skylight was placed in the middle of the ceiling. Due to current limitations in ALFA, it was not possible to import or create a diffuse glazing material for the skylight. In order to emulate the effects of a diffuse skylight, the sky conditions were set to overcast for all the simulation dates within the study, and the same clear glazing was used for the skylight as the windows from the original hypothetical office model. While this is not a very accurate way to simulate diffuse materials due to a multitude of factors including the altered spectral quality of the sky, this study still yielded valuable

results.

The most significant finding from this study was the change in melanopic illuminance due to the orientation of the sensor with the skylight. Sensors facing towards the skylight maintained values over 240 EML up to 16ft from the edge of the skylight, while sensors facing away from the skylight maintained values over 240 EML only 1 ft from the edge of the skylight. This finding indicates a very strong correlation between orientation of view to the skylight and circadian potential.

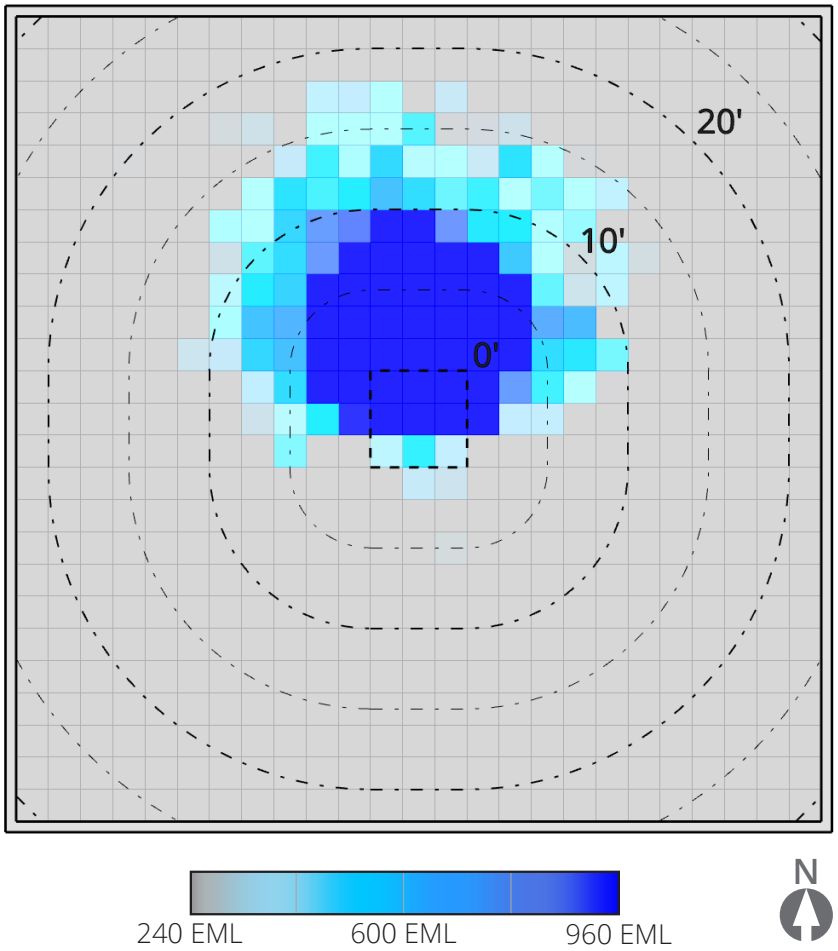


Figure 5.18. Skylight sensor grid visualizations, September 21st, 12pm, overcast

6. Conclusions

Analysis of the quantitative data from both the case studies and the simulations indicates that natural light can be a significant source of melanopic illuminance within the built environment, but only if it is effectively used. Both the case studies and the simulations identified a selection of architectural parameters that affect the circadian potential of a space. Most of these parameters can and must be identified early in the design process in order to account for their effects and maximize the circadian potential within spaces that will be occupied for prolonged periods during the day. Spaces such as offices, classrooms, and healthcare facilities require sufficient melanopic illuminance to entrain the circadian rhythms of their occupants, and the ideal source of that illuminance is daylight. By generating guidelines that can help designers make decisions at the earliest stages of the design process, it will be possible to maximize the potential for daylight-driven circadian lighting within these spaces.

6.1. Potential Guidelines

The study of the effects of the selection of architectural parameters isolated in the simulations revealed some key potential guidelines and recommendations that can be made for architects and designers developing spaces that require circadian lighting. The first guideline comes from the finding that obstructions to views of the sky can have a significant effect on circadian potential.

Guideline 1:

Study the context of the project and identify potential obstructions to views of the sky to account for their affect on circadian stimulus. If possible, arrange the program elements that require circadian stimulus to minimize obstructed views to the sky.

While this is also good daylight practice, it is worth noting due to the substantial effect on circadian potential that can override other factors.

Guideline 2:

Shading strategies that obstruct exterior views or views of the sky should be avoided. Static shading devices, horizontal blinds, or glare storage strategies can be used to maximize daylight-driven circadian potential.

This guideline was derived from the findings of the shading device simulations. These determined that shading strategies such as awnings and horizontal blinds that reduce glare without obstructing the view through the window had little to no impact on circadian potential, while shading devices that significantly alter the light entering through the window, such as electrochromic glass, have a substantial adverse effect on circadian potential.

Guideline 3:

Workstations or seating areas over 20ft from a window should be oriented to face the nearest window to maximize the effectiveness of daylight in providing circadian stimulus.

As observed in both the case studies and the simulations, orientation of view of the occupant in relation to the nearest window can have a very significant impact on circadian stimulus. This guideline asserts that 20 ft is a reasonable metric for determining when orientation of view becomes a significant factor in the daylight-driven circadian stimulus and suggests an orientation that could maximize potential. It is worth noting however that other factors may alter this metric and further analysis would be required to further tune the space to maximize the effective use of daylight for circadian stimulus.

> **Guideline 4:**
> In lieu of vertical glazing, orient workstations or seating areas towards skylights in order to maximize daylight-driven circadian stimulus.

The skylight simulations revealed that circadian stimulus from skylights is only effective for occupants that have the skylight within their frame of view. This guideline is intended to suggest that, if exterior views are not available or significant visual obstructions exist for other sources of daylight, then it is necessary to ensure that skylights are within the frame of view of the occupants to maximize their effectiveness as sources of circadian stimulus.

6.2. Future Study

This thesis has only scratched the surface of the of the effect that various architectural parameters can have on daylight-driven circadian stimulus. Even so, it has found a wealth of information that will require further study. While

there is already a significant body of work that explores the effect daylighting in the built environment, their findings do not always directly apply to daylight-driven circadian lighting. Due to this, it is necessary to complete further study on this subject to better understand the effects of the built environment on daylight-driven circadian stimulus and find ways more effectively used daylight for circadian stimulus in spaces that require it.

Some areas for further study found in this thesis include: The quantifiable effect of obstructions to views of the sky on daylight-driven circadian lighting, the relationship between room depth and daylight-driven circadian light, a further analysis of the correlation between the head height of the window and the depth of potential for daylight-driven circadian stimulus, and a complete study on the effectiveness of skylights in providing circadian stimulus.

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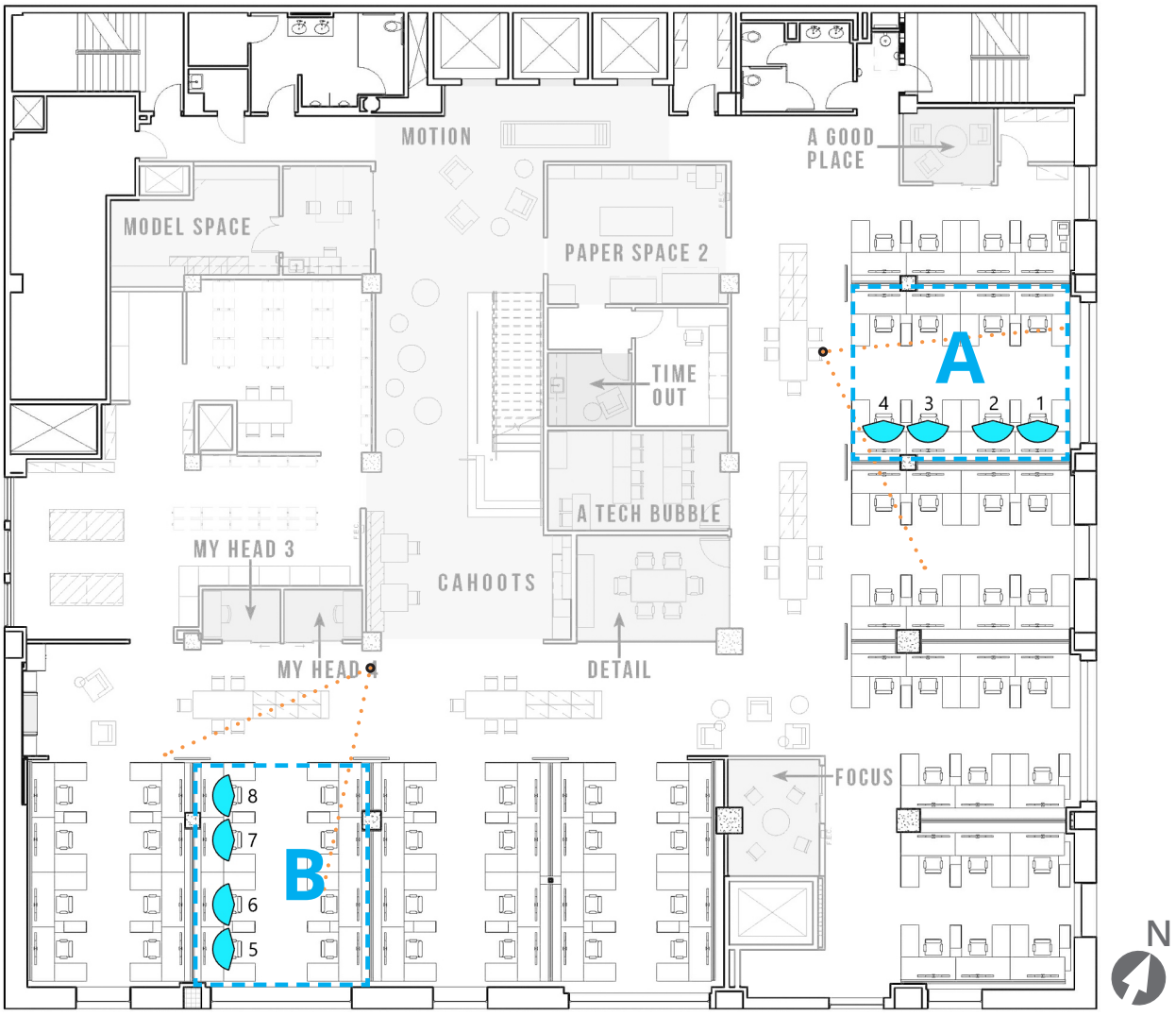
Appendix A: Case Study Analysis Results

Case Study 1 - Ankrom Moisan Office

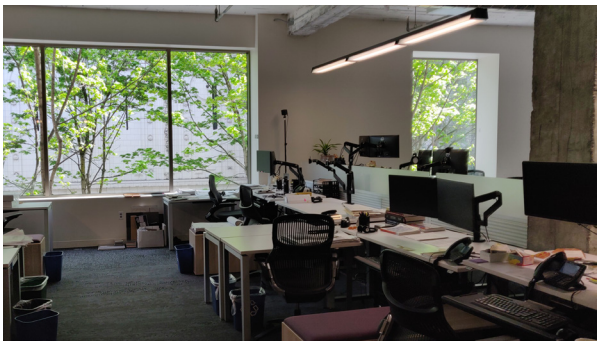
Floor Plan

Workstation View Angle: 

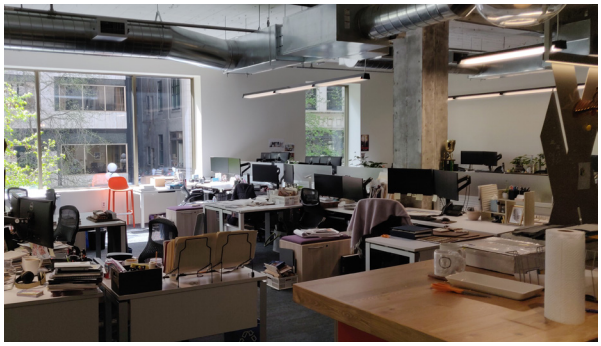


Office Photos

ZONE A

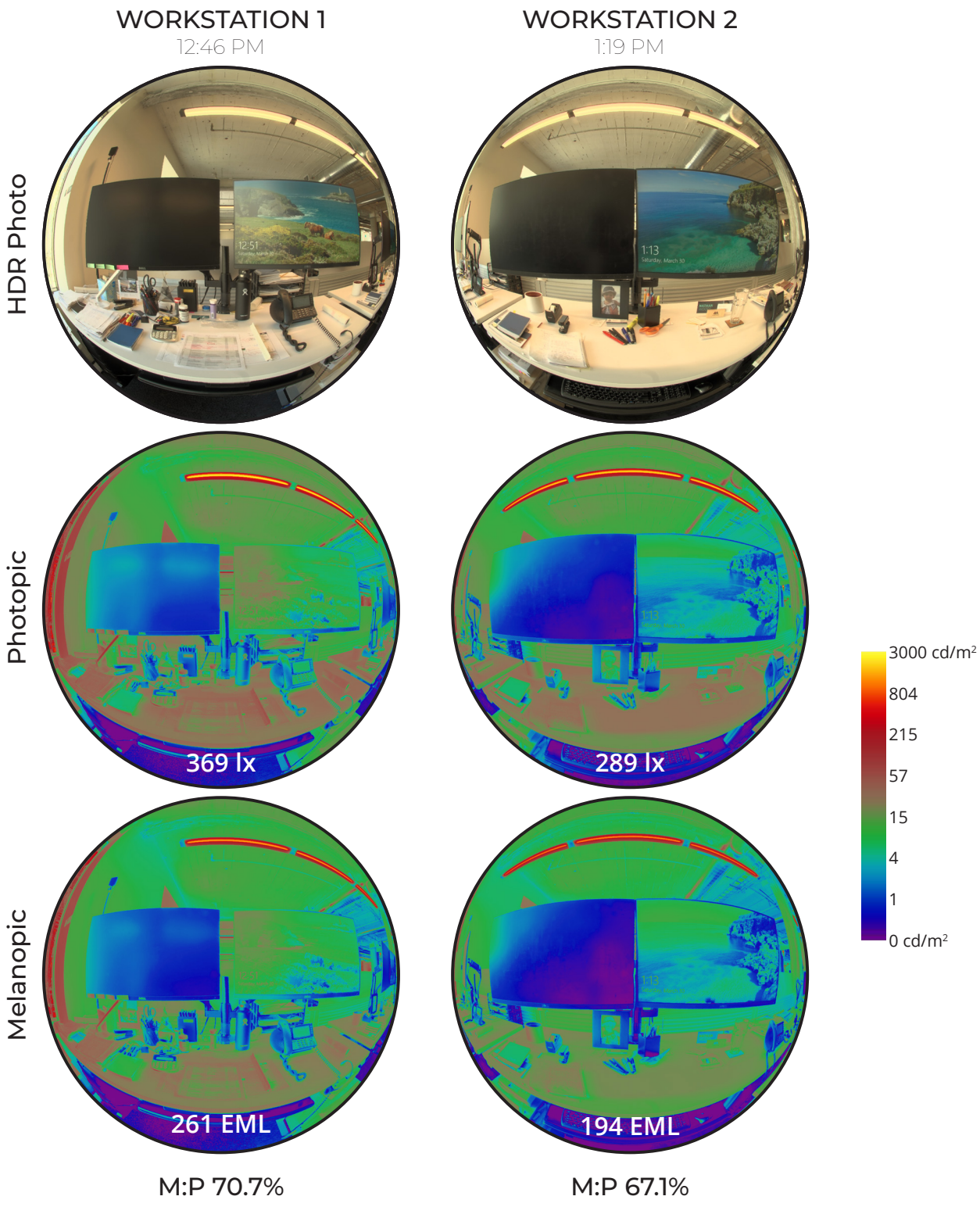


ZONE B



Study 1.1 - Zone A - All Lights On

Date: Saturday, March 30th
Weather: Clear
Global Horizontal Solar Irradiance: 520 w/m²
Ambient Lighting Color Temp: 3500K



M:P 70.7%

M:P 67.1%

Study 1.1 - Zone A - All Lights On

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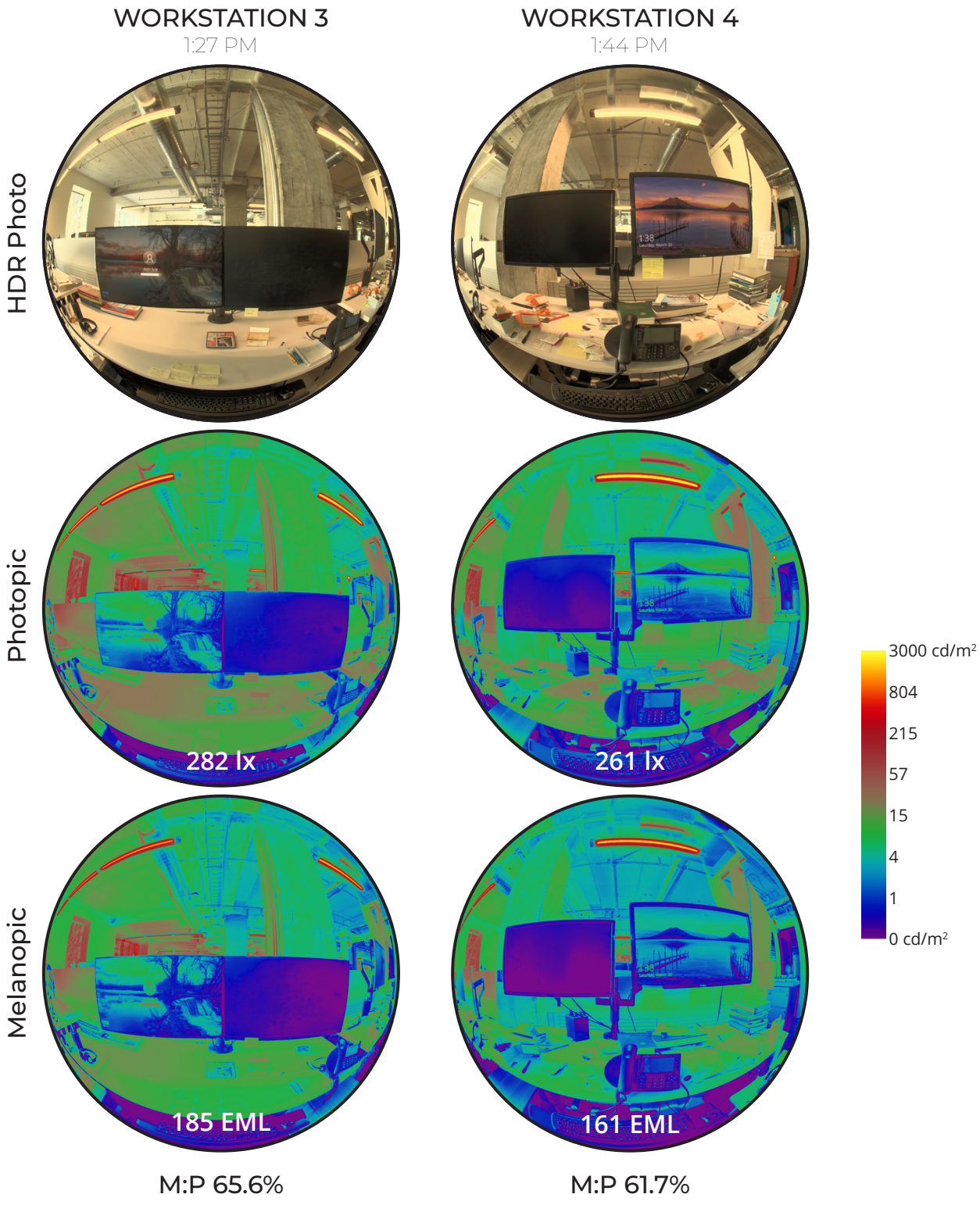
Ambient Lighting Color Temp: 3500K



Study 1.1 - Zone B - All Lights On

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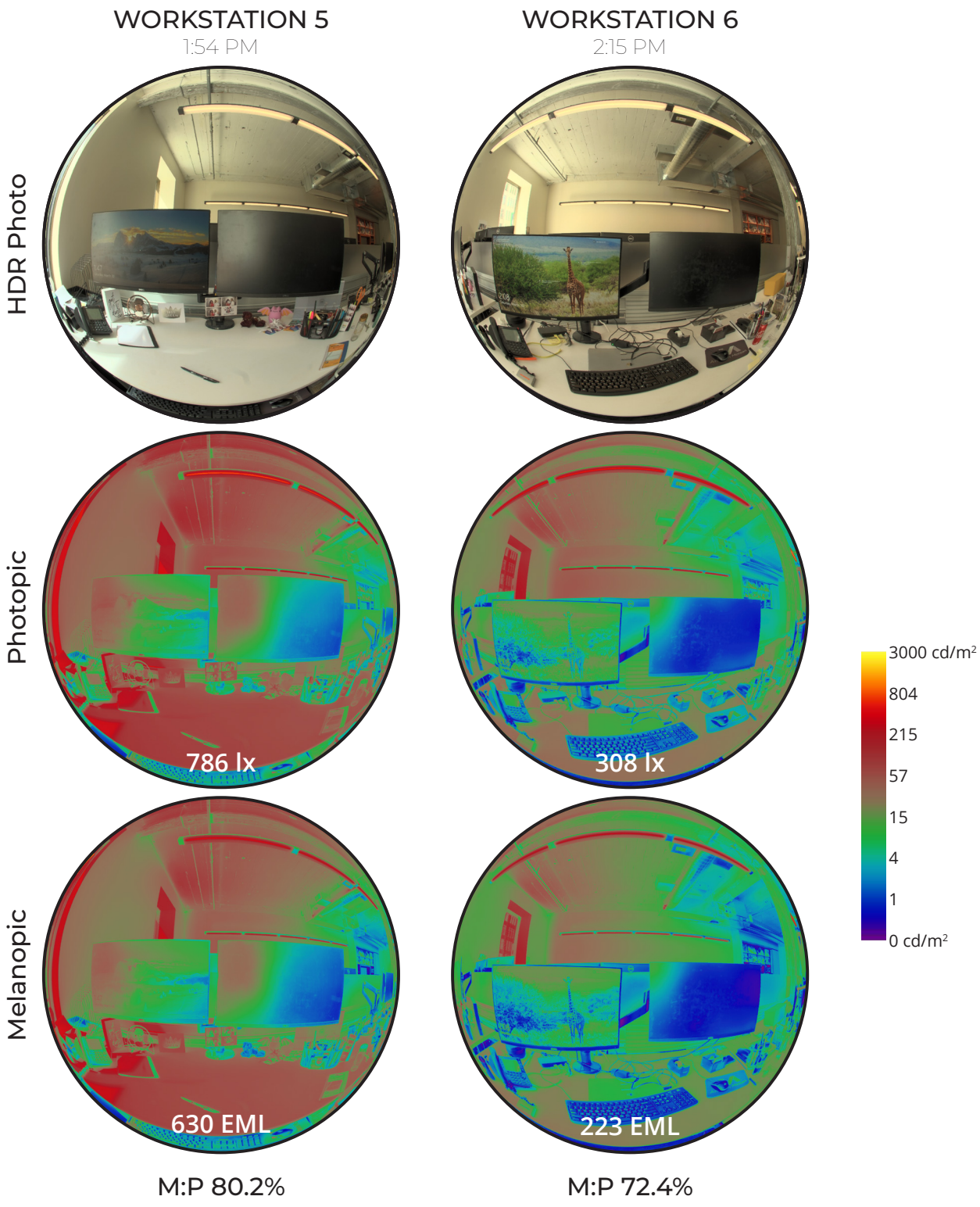

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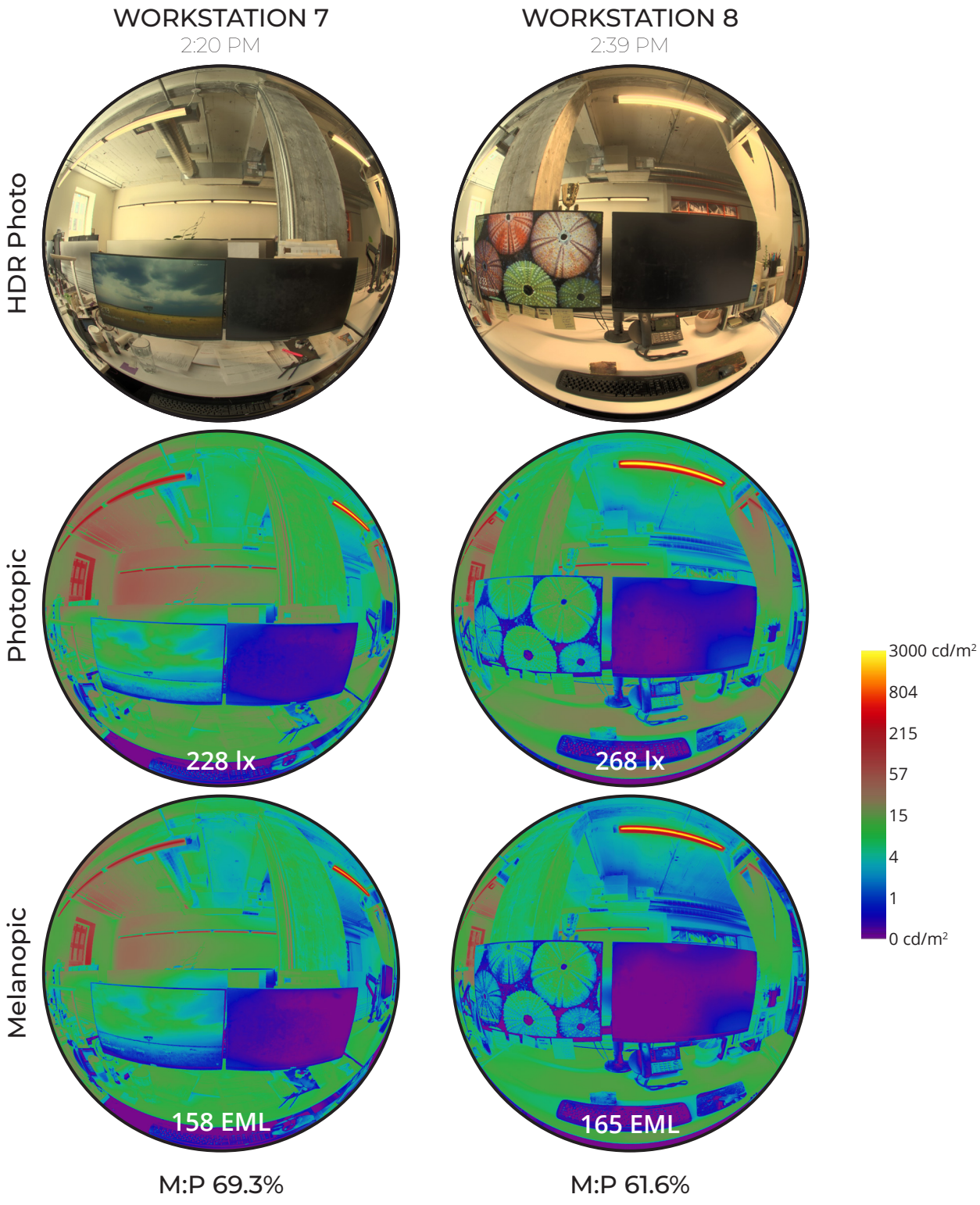
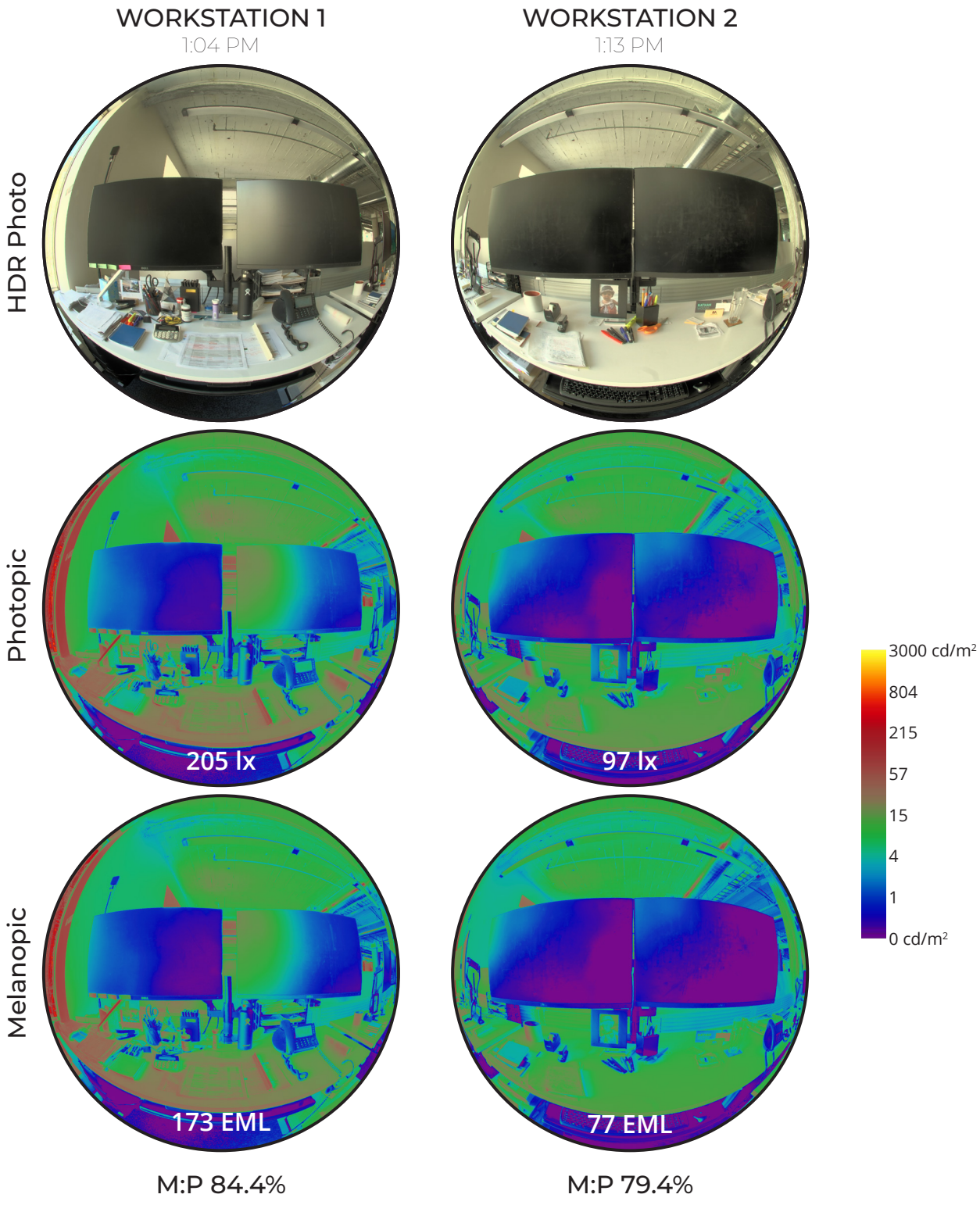
Ambient Lighting Color Temp: 3500K



Study 1.1 - Zone A - Daylight Only

Date: Saturday, March 30th
Weather: Clear
Global Horizontal Solar Irradiance: 520 w/m²
Ambient Lighting Color Temp: 3500K

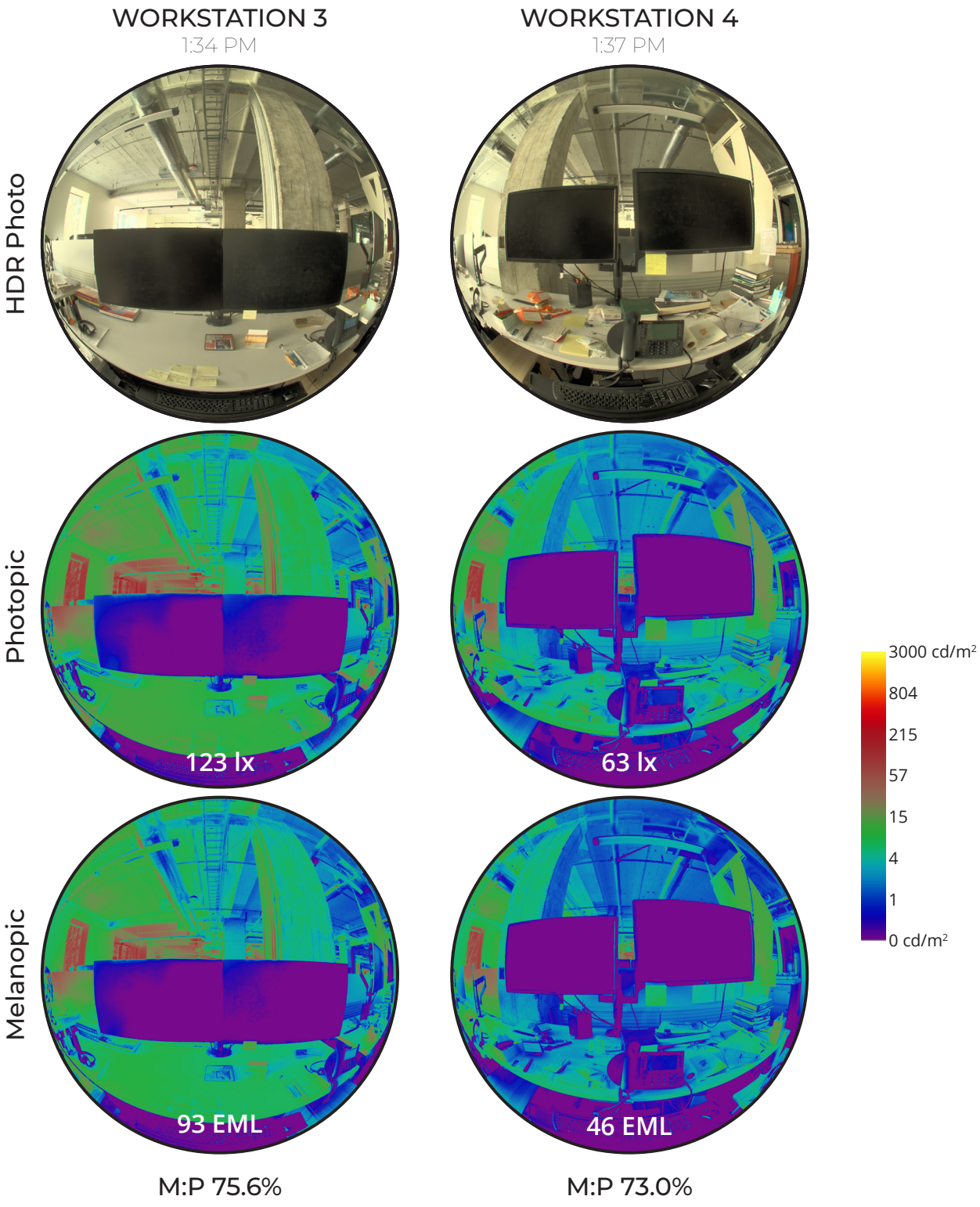


M:P 84.4%

M:P 79.4%

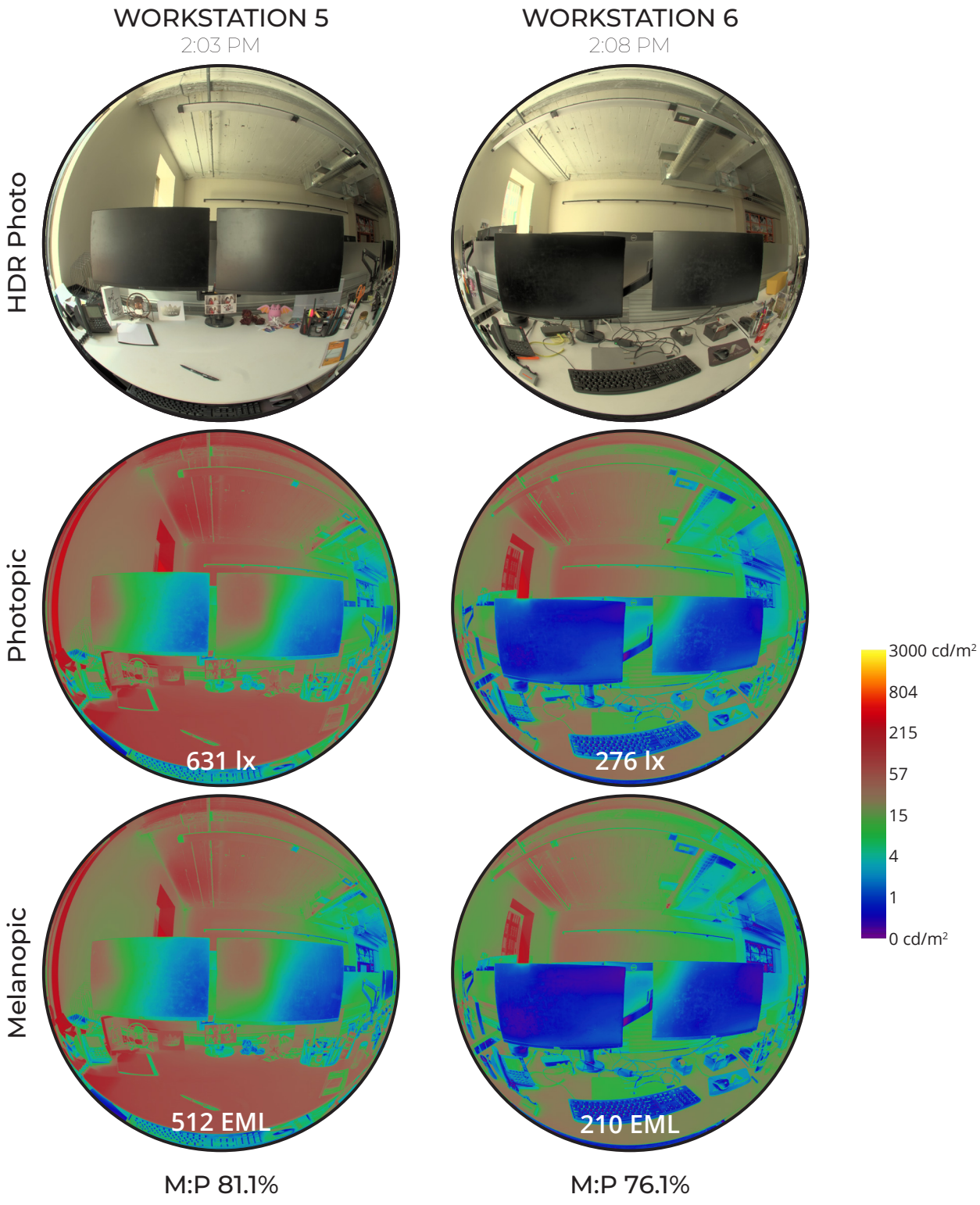
Study 1.1 - Zone A - Daylight Only

Date: Saturday, March 30th
Weather: Clear
Global Horizontal Solar Irradiance: 520 w/m²
Ambient Lighting Color Temp: 3500K



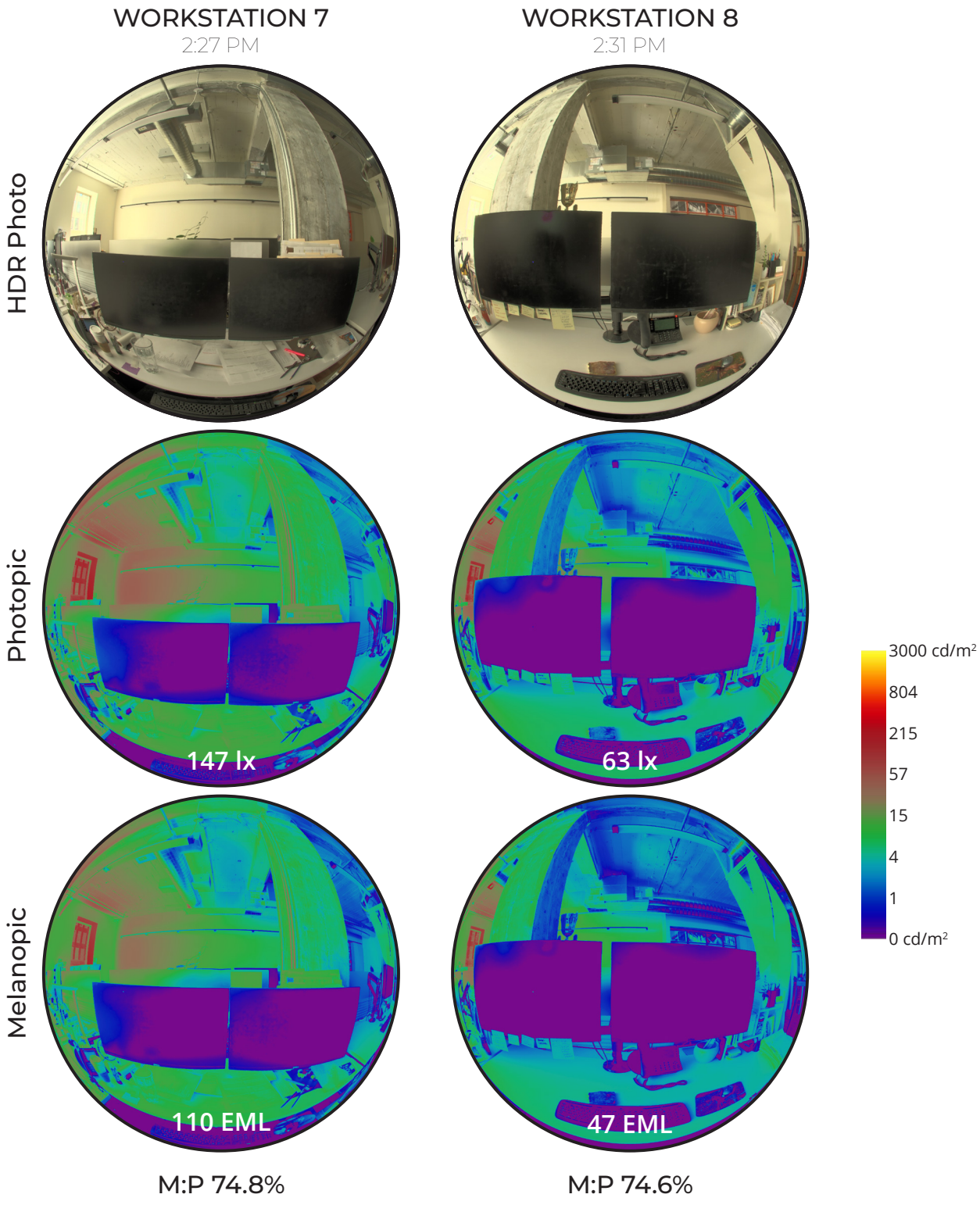
Study 1.1 - Zone B - Daylight Only

Date: Saturday, March 30th
Weather: Clear
Global Horizontal Solar Irradiance: 520 w/m²
Ambient Lighting Color Temp: 3500K



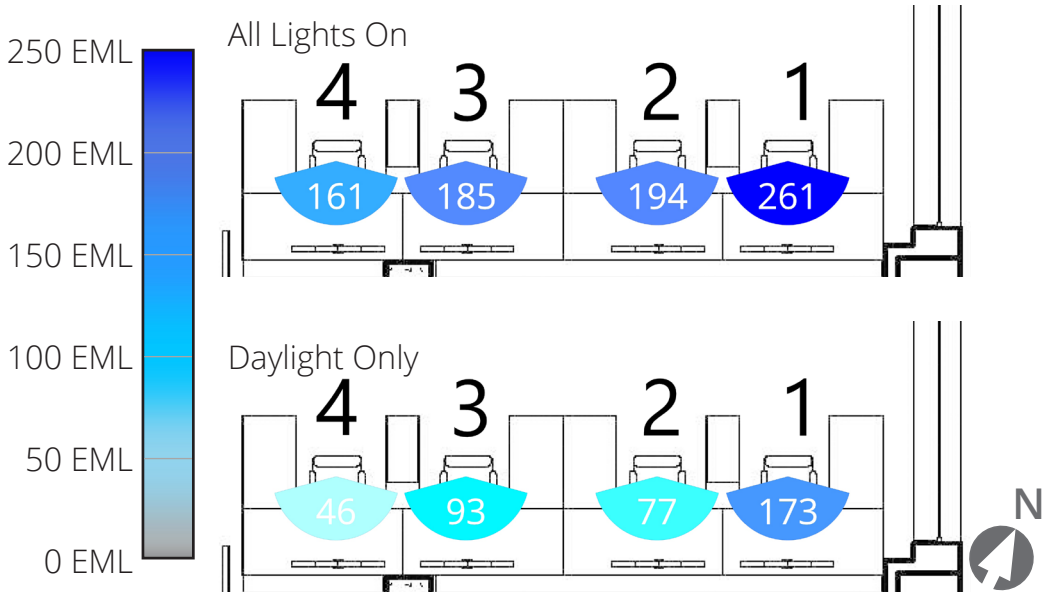
Study 1.1 - Zone B - Daylight Only

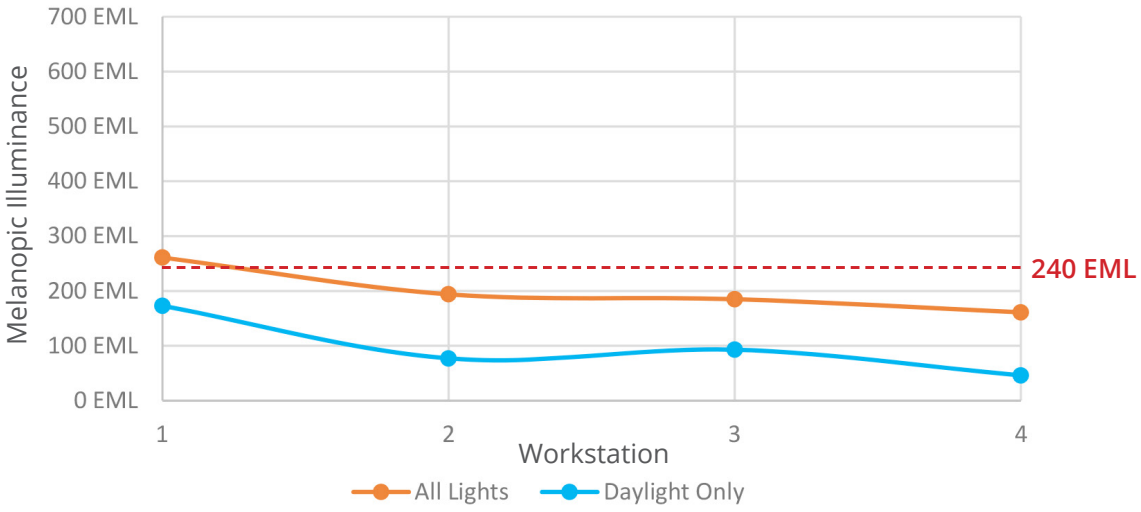
Date: Saturday, March 30th
Weather: Clear
Global Horizontal Solar Irradiance: 520 w/m²
Ambient Lighting Color Temp: 3500K



Study 1.1 - Zone A - Melanopic Illuminance

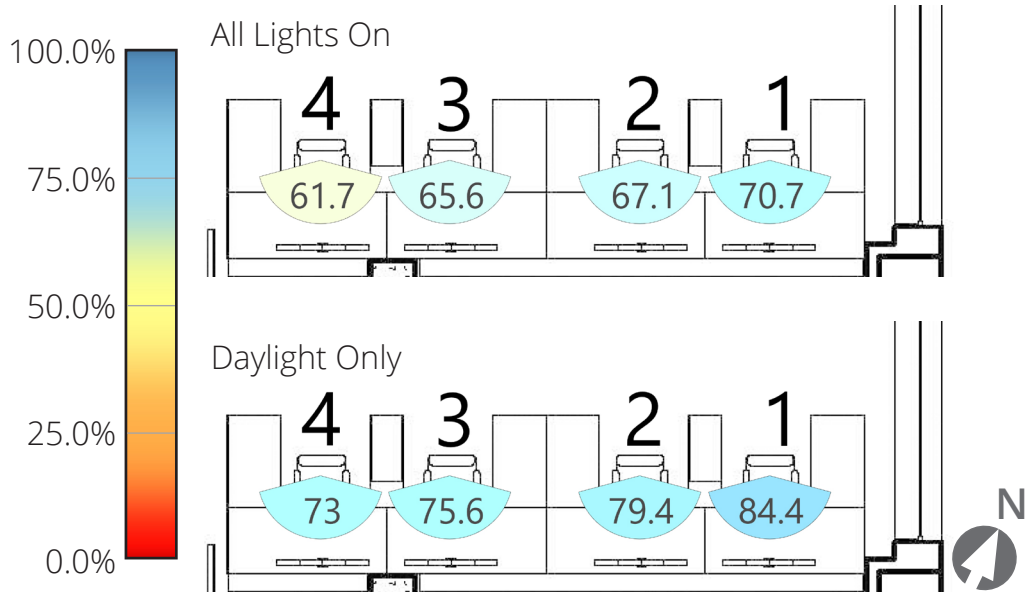
Date: Saturday, March 30th
Weather: Clear
Global Horizontal Solar Irradiance: 520 w/m²
Ambient Lighting Color Temp: 3500K

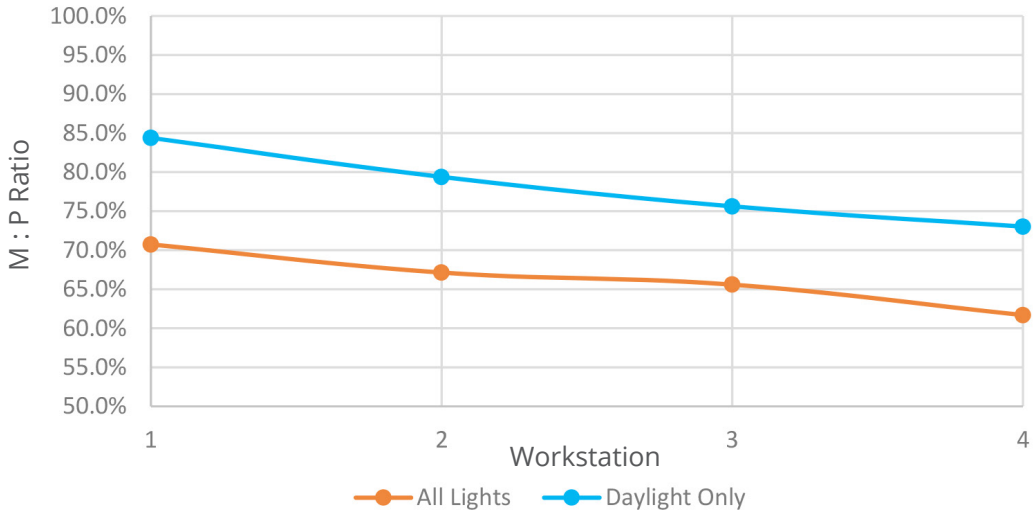




Study 1.1 - Zone A - Melanopic : Photopic Ratio

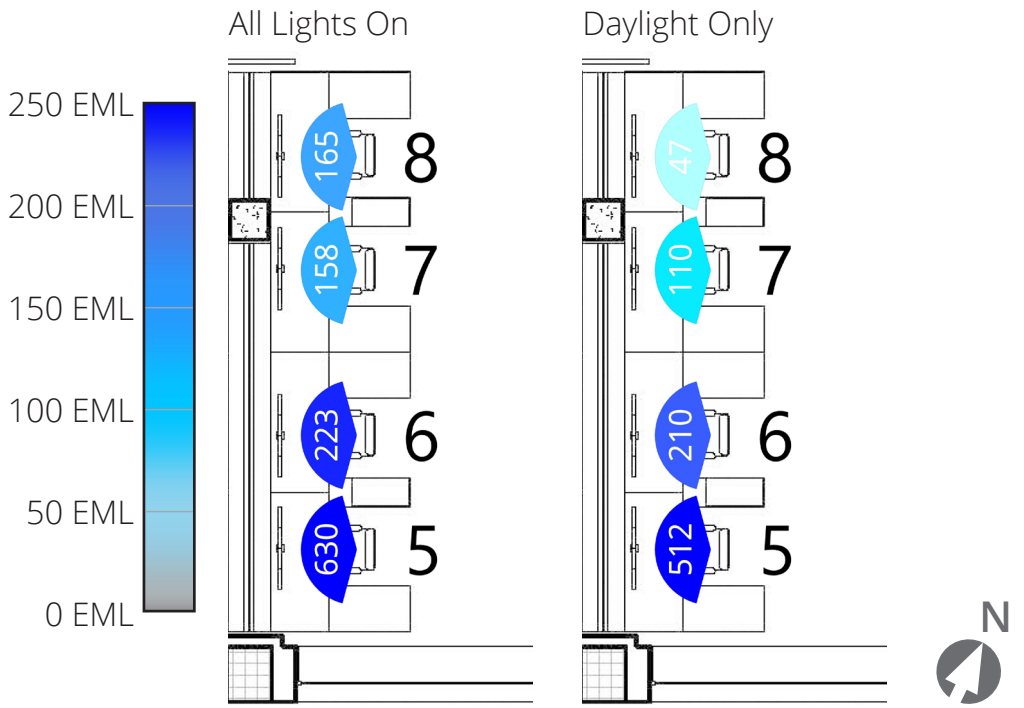
Date: Saturday, March 30th
Weather: Clear
Global Horizontal Solar Irradiance: 520 w/m²
Ambient Lighting Color Temp: 3500K

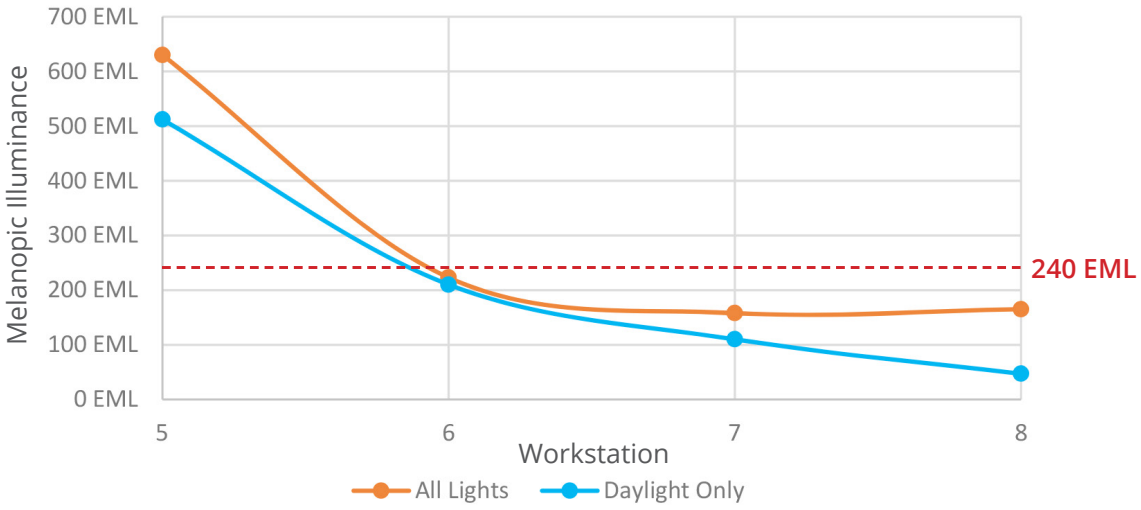




Study 1.1 - Zone B - Melanopic Illuminance

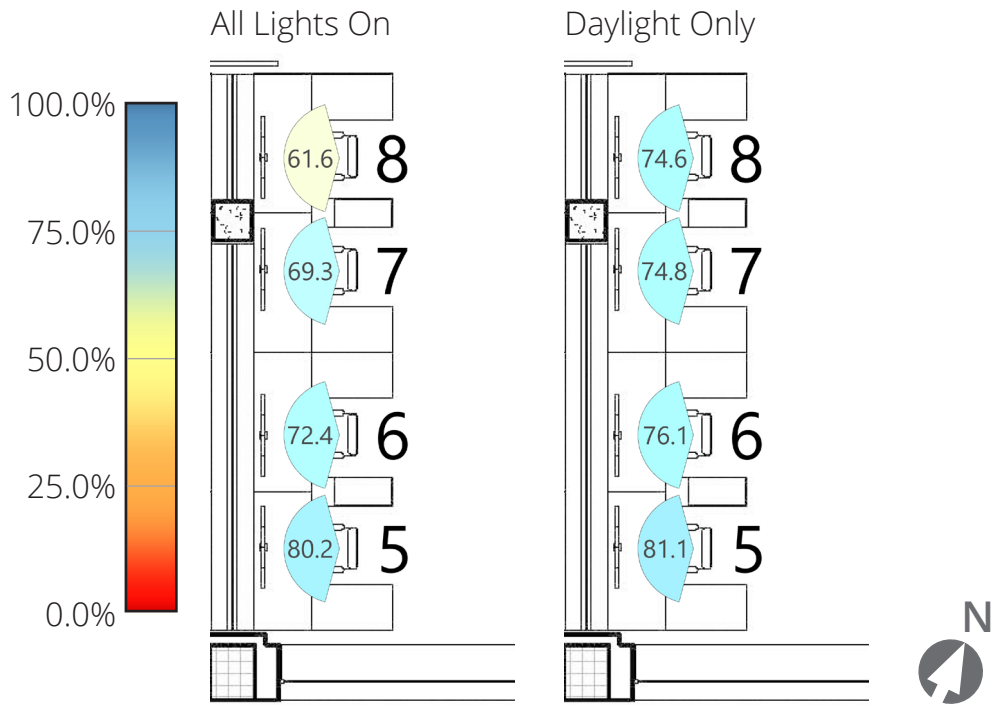
Date: Saturday, March 30th
Weather: Clear
Global Horizontal Solar Irradiance: 520 w/m²
Ambient Lighting Color Temp: 3500K

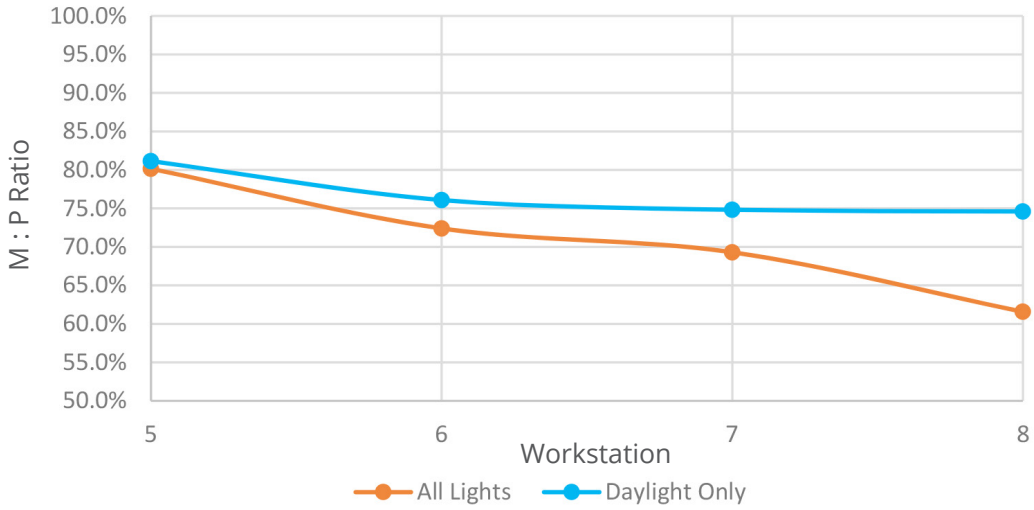




Study 1.1 - Zone B - Melanopic : Photopic Ratio

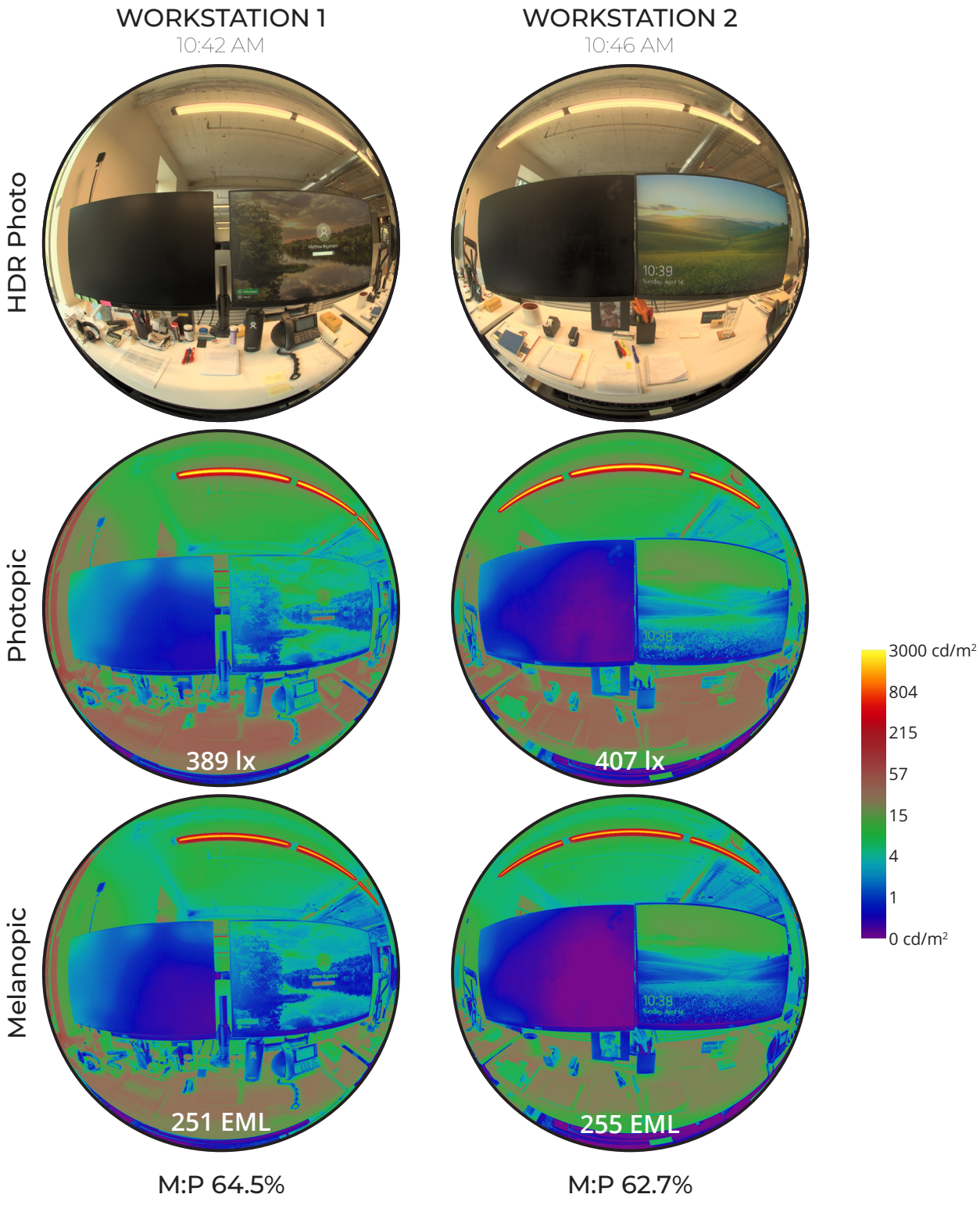
Date: Saturday, March 30th
Weather: Clear
Global Horizontal Solar Irradiance: 520 w/m²
Ambient Lighting Color Temp: 3500K





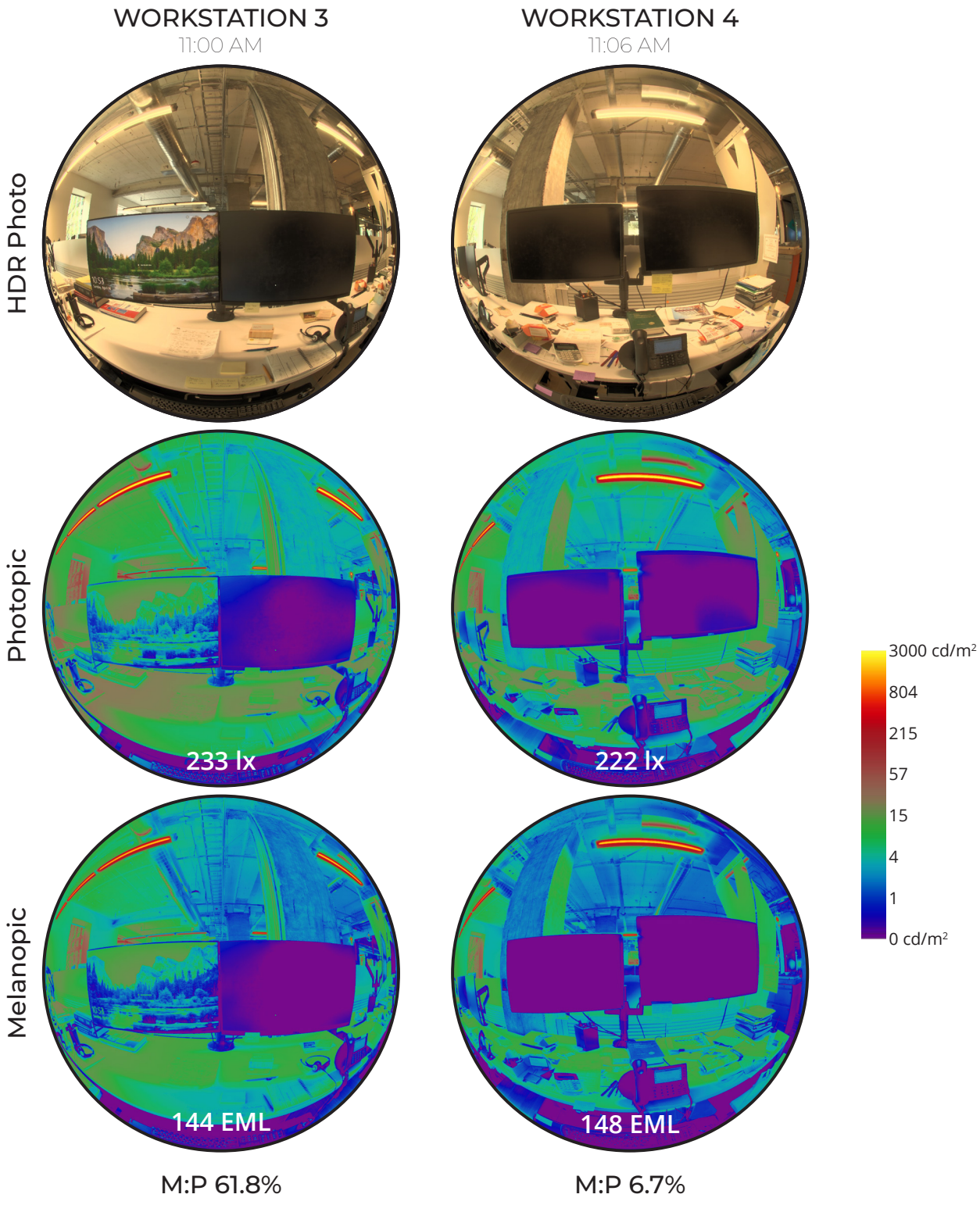
Study 1.2 - Zone A - All Lights On

Date: Sunday, April 14th
Weather: Overcast
Global Horizontal Solar Irradiance: 211 w/m²
Ambient Lighting Color Temp: 3500K



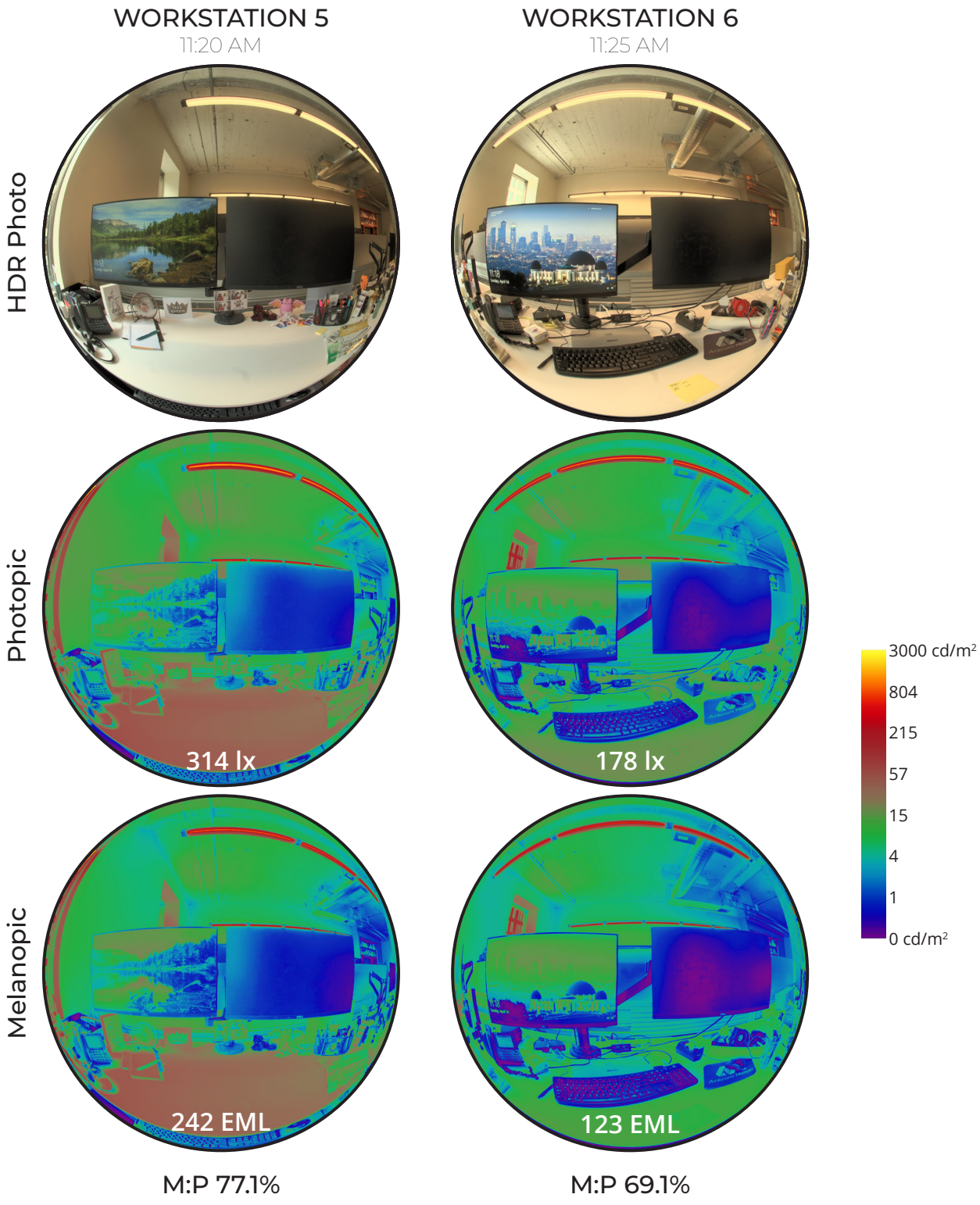
Study 1.2 - Zone A - All Lights On

Date: Sunday, April 14th
Weather: Overcast
Global Horizontal Solar Irradiance: 211 w/m²
Ambient Lighting Color Temp: 3500K



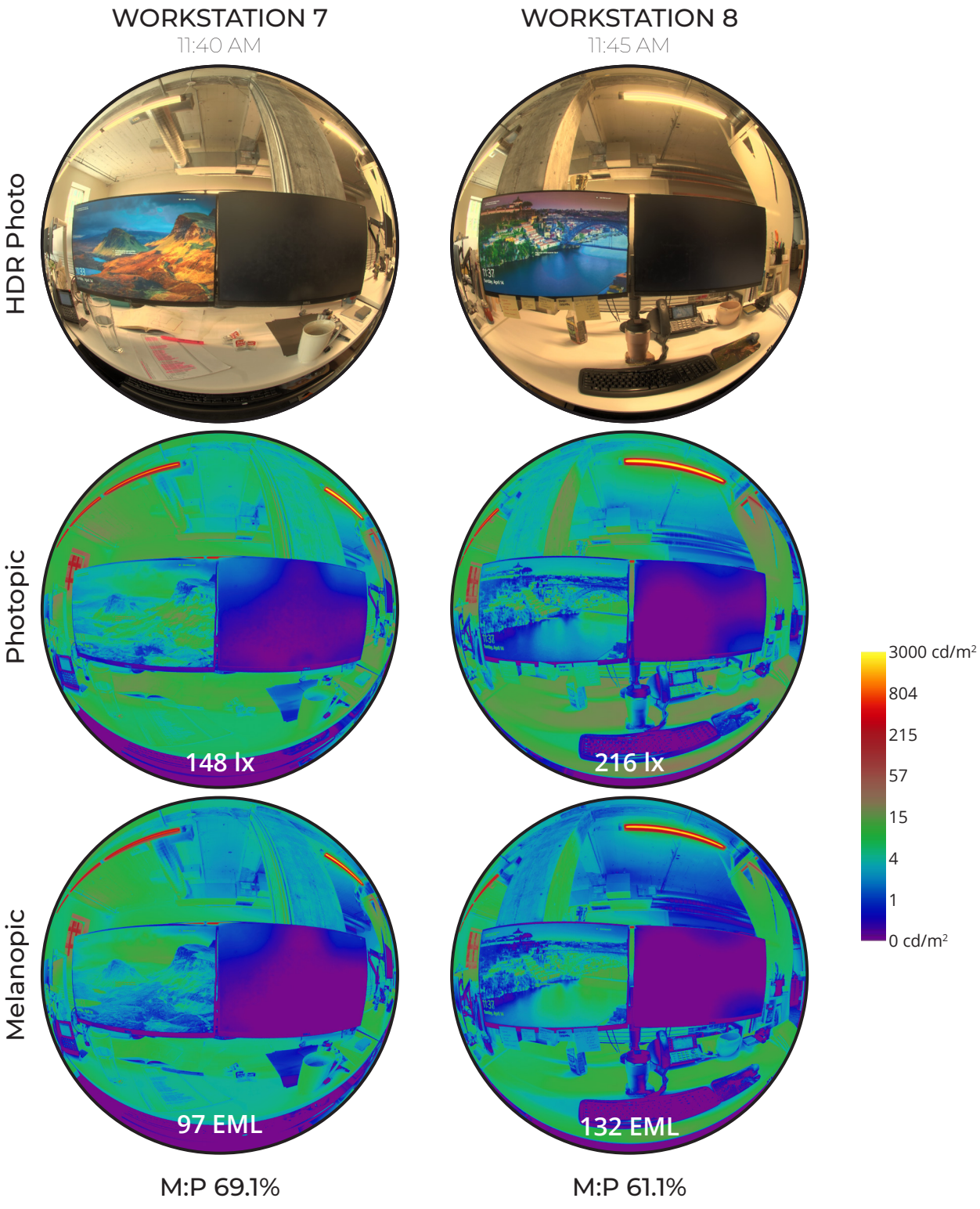
Study 1.2 - Zone A - All Lights On

Date: Sunday, April 14th
Weather: Overcast
Global Horizontal Solar Irradiance: 211 w/m²
Ambient Lighting Color Temp: 3500K



Study 1.2 - Zone B - All Lights On

Date: Sunday, April 14th
Weather: Overcast
Global Horizontal Solar Irradiance: 211 w/m²
Ambient Lighting Color Temp: 3500K

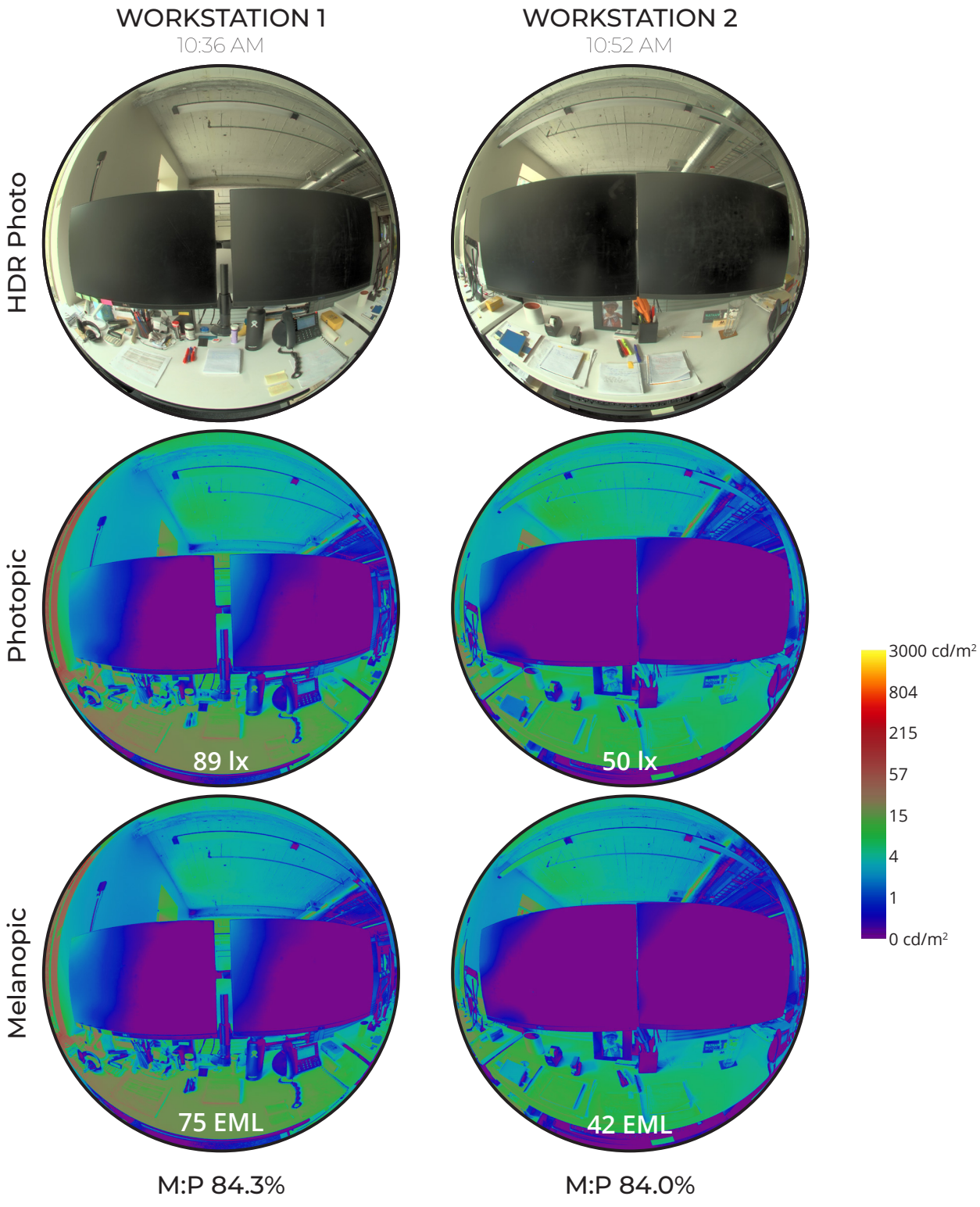


M:P 69.1%

M:P 61.1%

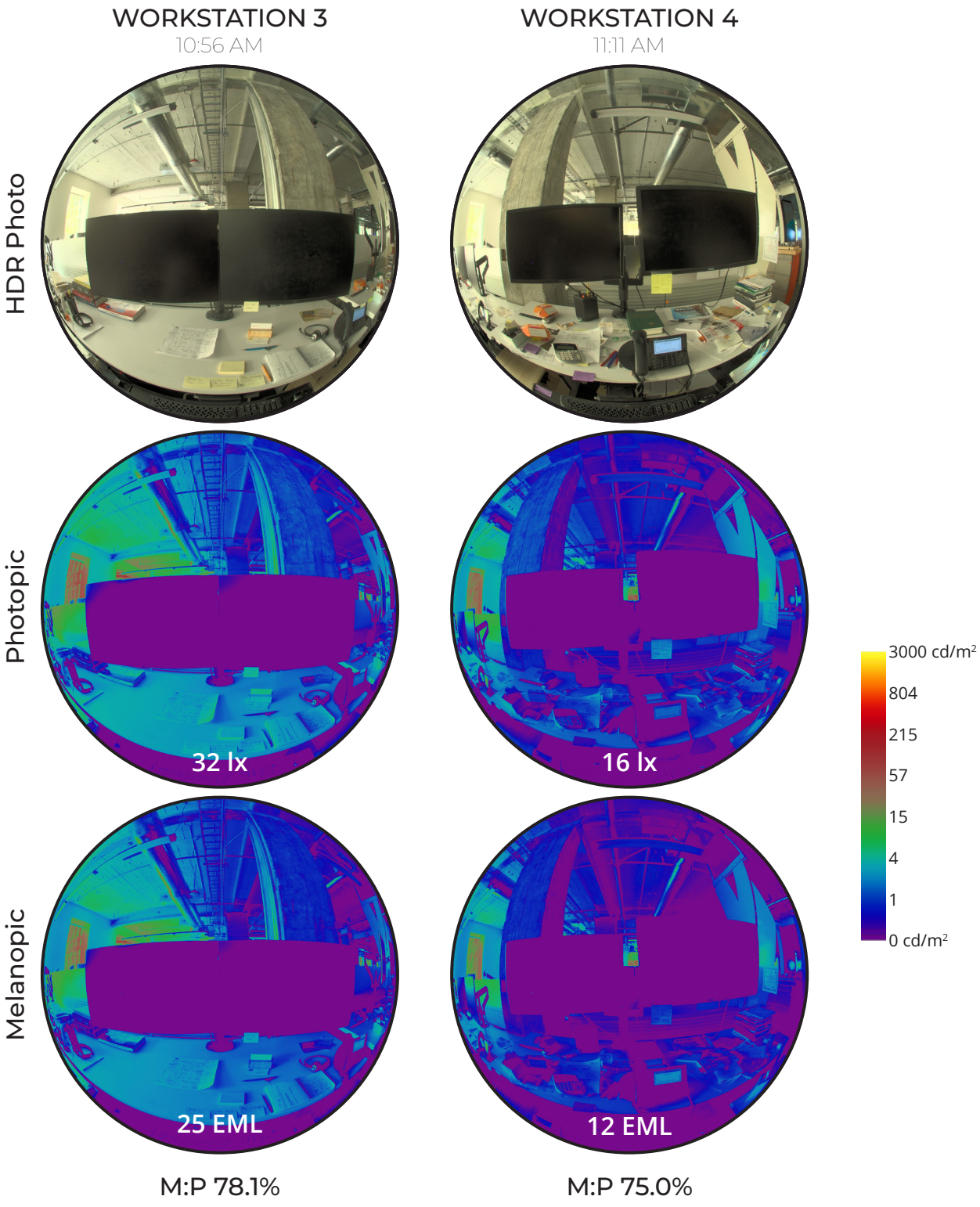
Study 1.2 - Zone A - Daylight Only

Date: Sunday, April 14th
Weather: Overcast
Global Horizontal Solar Irradiance: 211 w/m²
Ambient Lighting Color Temp: 3500K



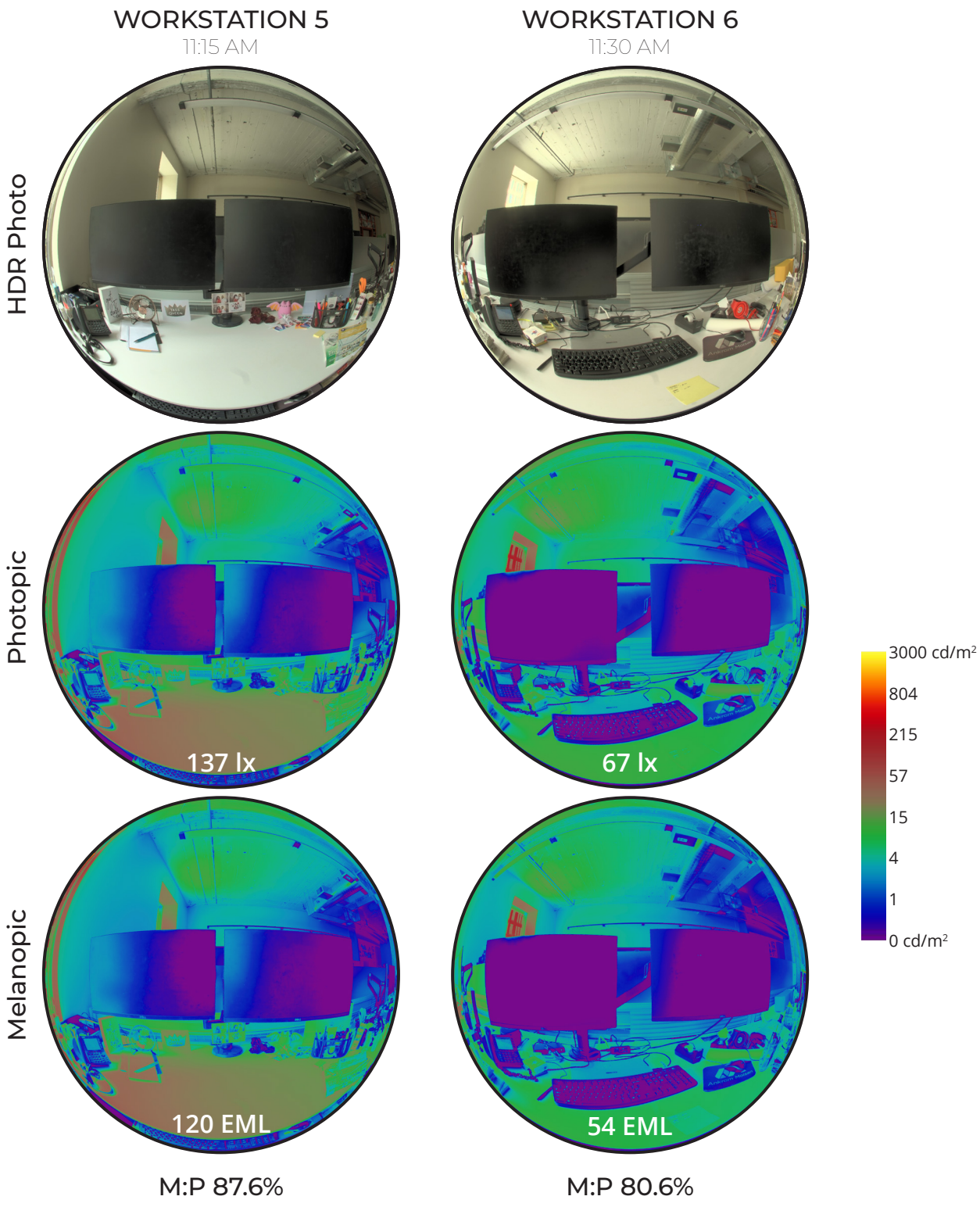
Study 1.2 - Zone A - Daylight Only

Date: Sunday, April 14th
Weather: Overcast
Global Horizontal Solar Irradiance: 211 w/m²
Ambient Lighting Color Temp: 3500K



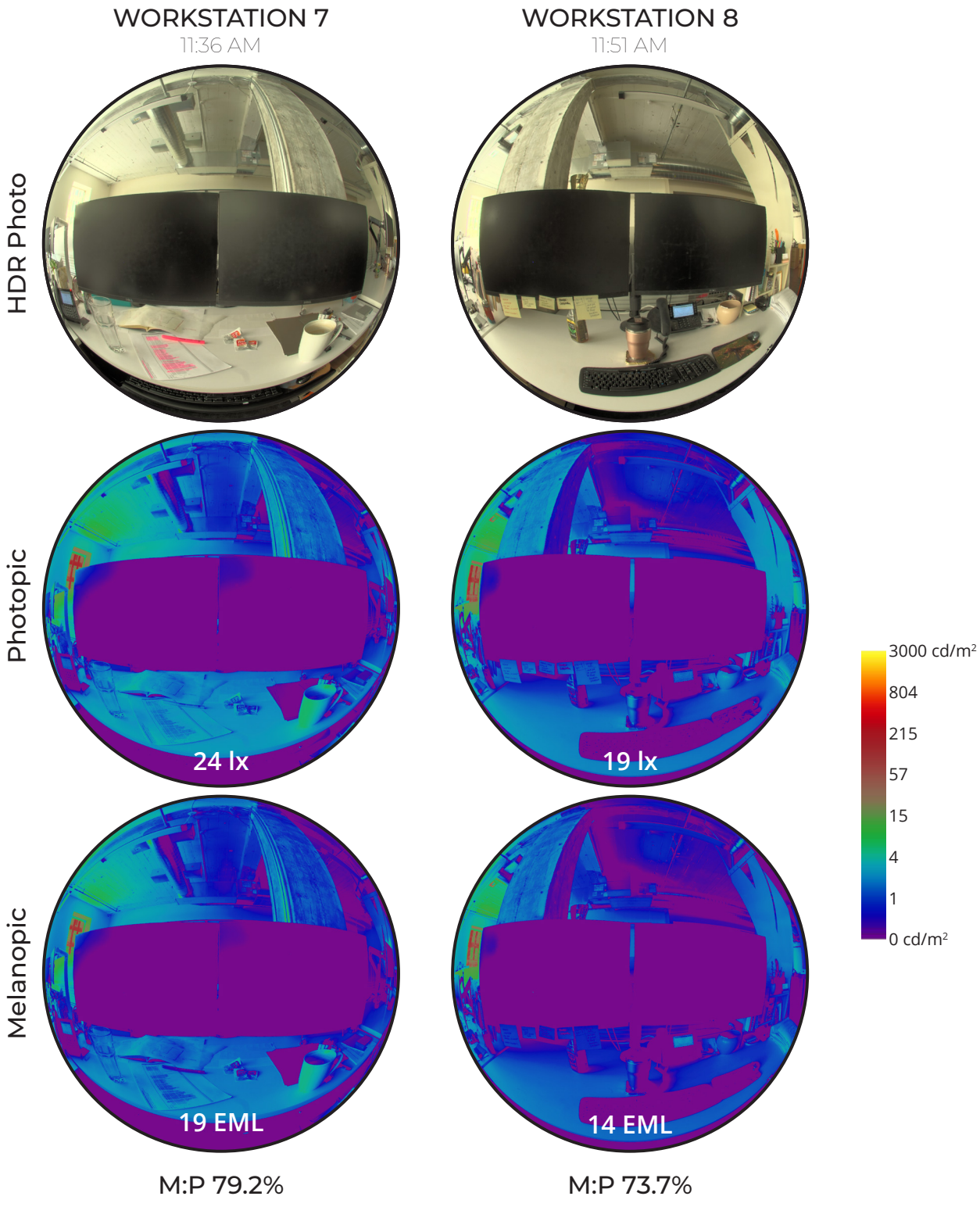
Study 1.2 - Zone B - Daylight Only

Date: Sunday, April 14th
Weather: Overcast
Global Horizontal Solar Irradiance: 211 w/m²
Ambient Lighting Color Temp: 3500K



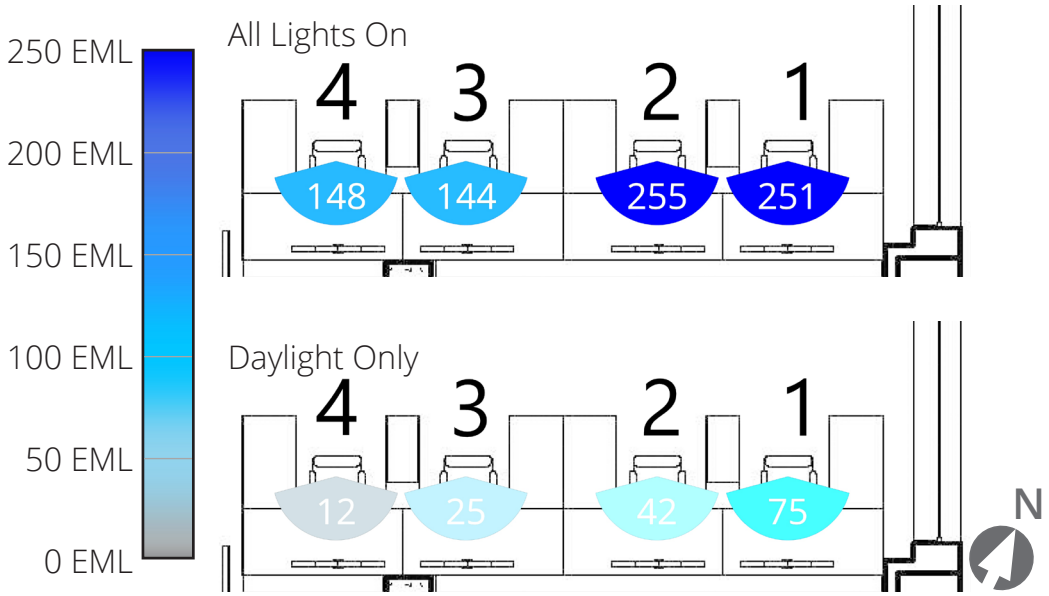
Study 1.2 - Zone B - Daylight Only

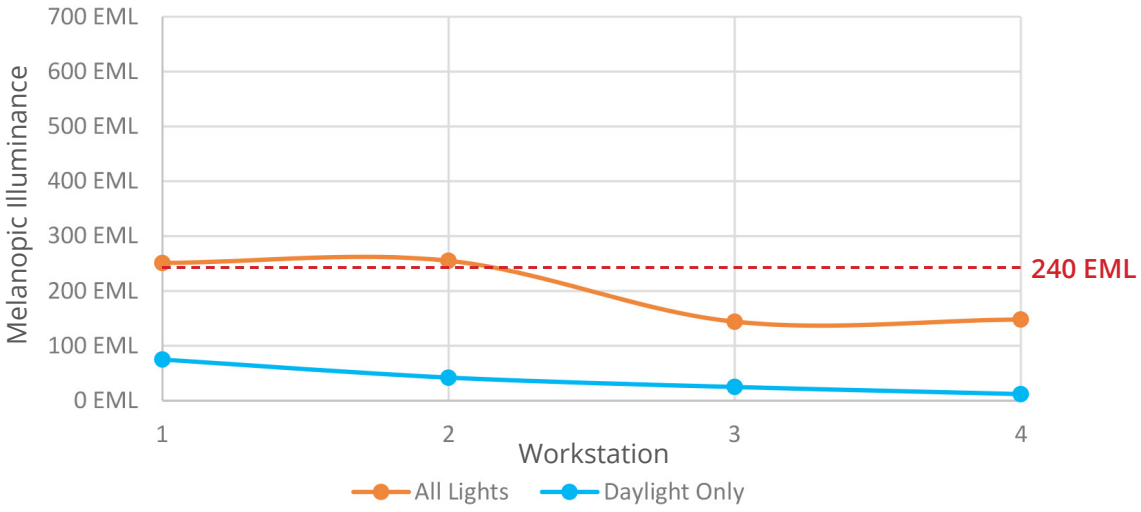
Date: Sunday, April 14th
Weather: Overcast
Global Horizontal Solar Irradiance: 211 w/m²
Ambient Lighting Color Temp: 3500K



Study 1.2 - Zone A - Melanopic Illuminance

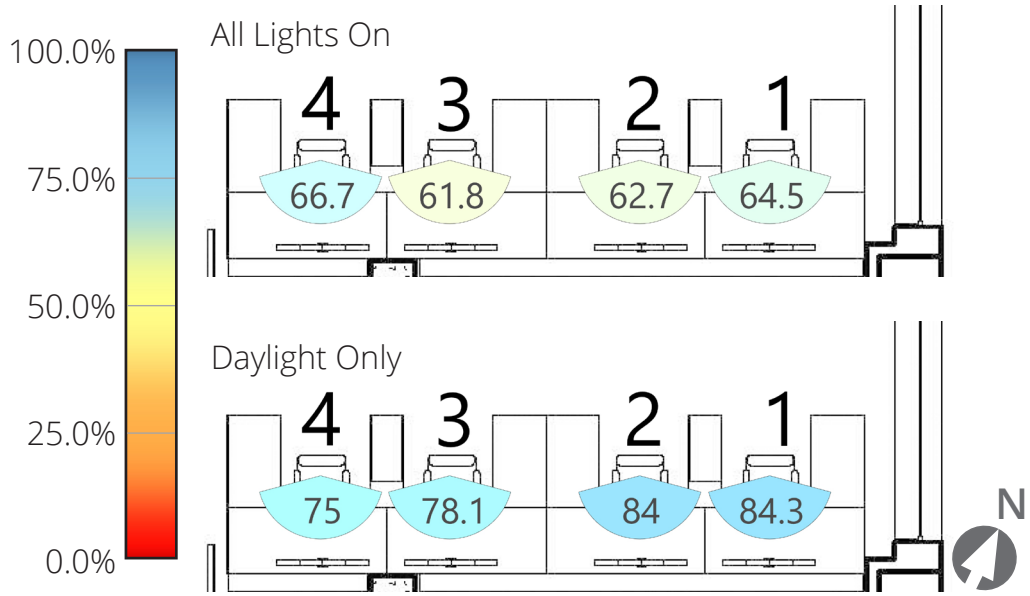
Date: Sunday, April 14th
Weather: Overcast
Global Horizontal Solar Irradiance: 211 w/m²
Ambient Lighting Color Temp: 3500K

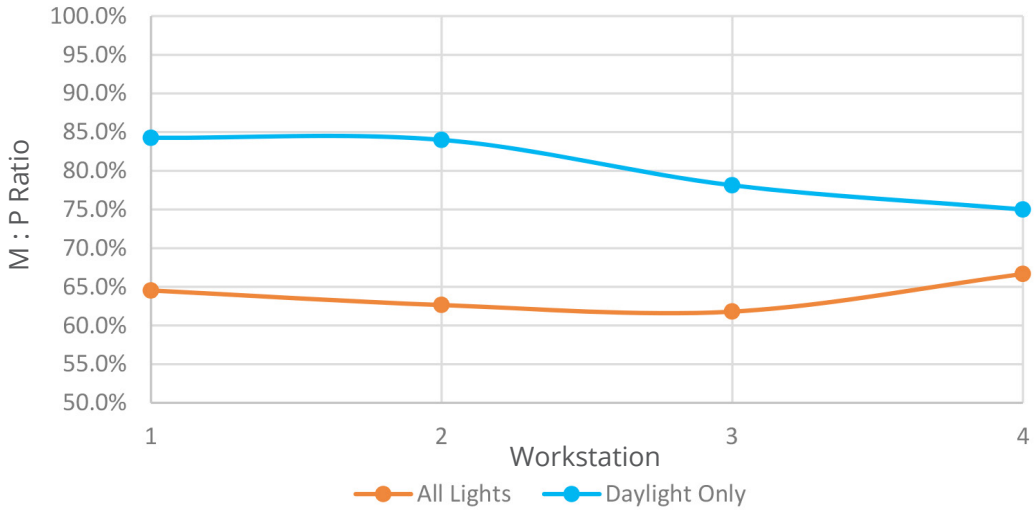




Study 1.2 - Zone A - Melanopic : Photopic Ratio

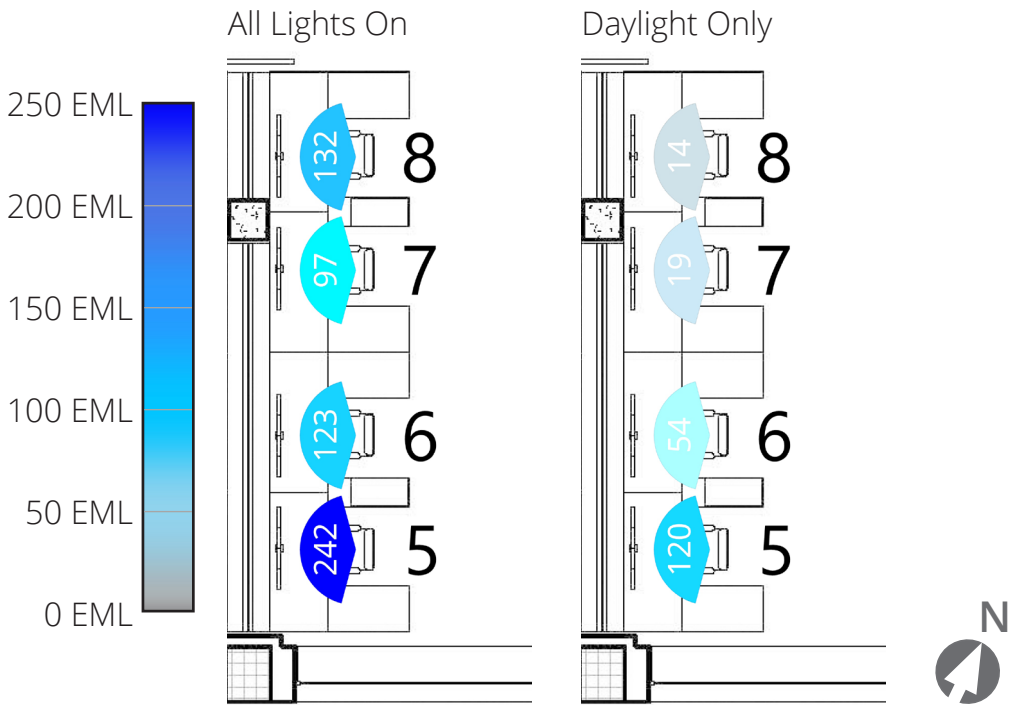
Date: Sunday, April 14th
Weather: Overcast
Global Horizontal Solar Irradiance: 211 w/m²
Ambient Lighting Color Temp: 3500K

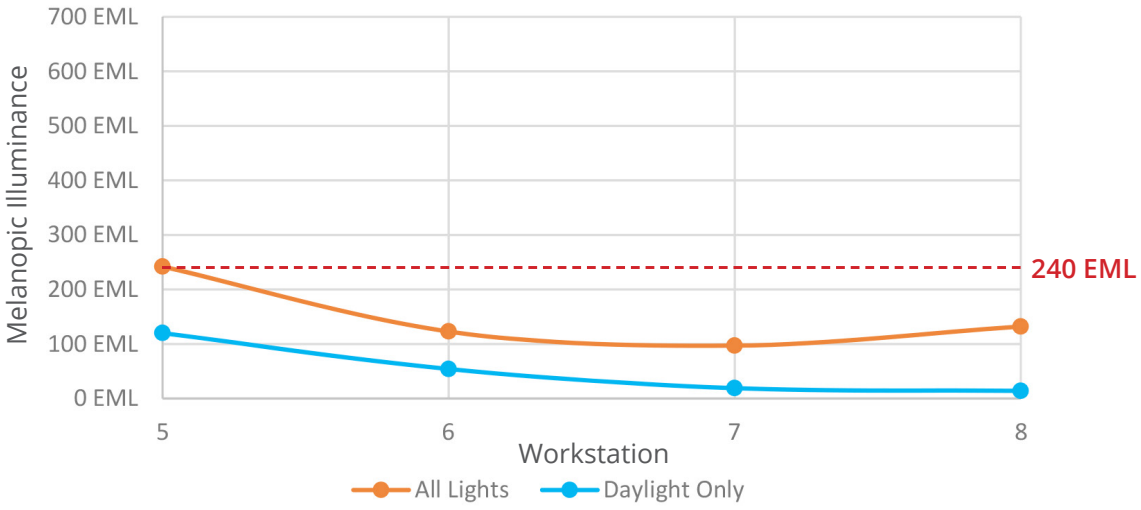




Study 1.2 - Zone B - Melanopic Illuminance

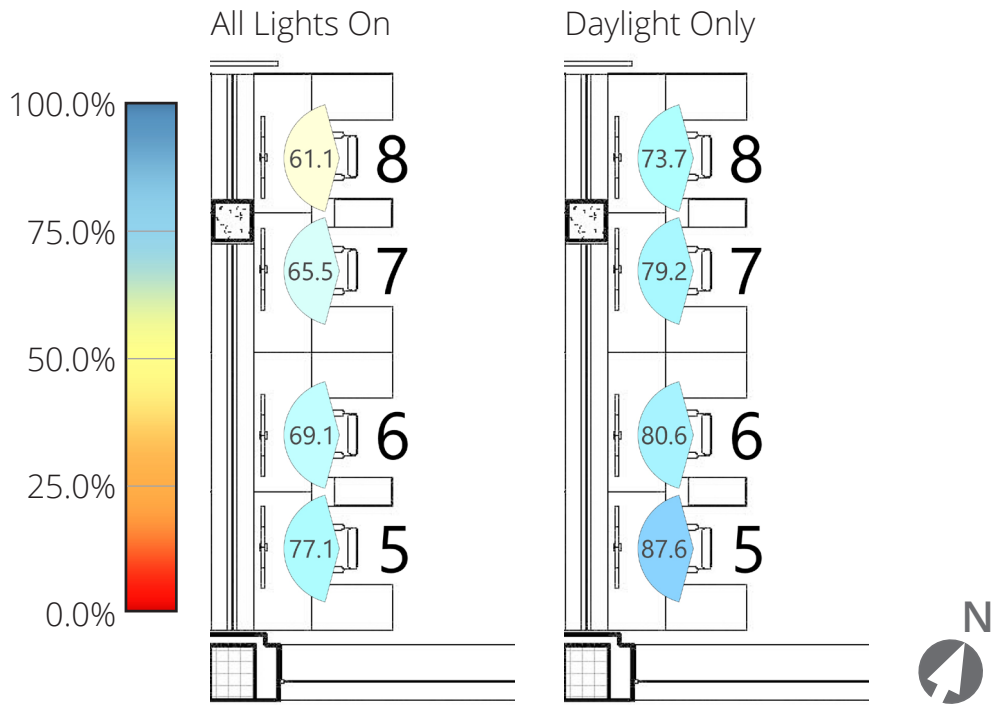
Date: Sunday, April 14th
Weather: Overcast
Global Horizontal Solar Irradiance: 211 w/m²
Ambient Lighting Color Temp: 3500K

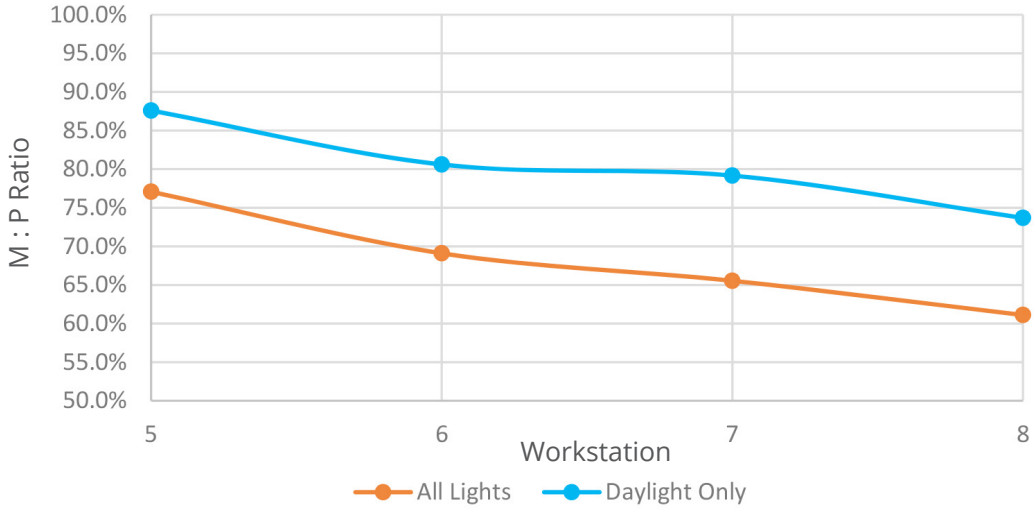




Study 1.1 - Zone B - Melanopic : Photopic Ratio

Date: Sunday, April 14th
Weather: Overcast
Global Horizontal Solar Irradiance: 211 w/m²
Ambient Lighting Color Temp: 3500K

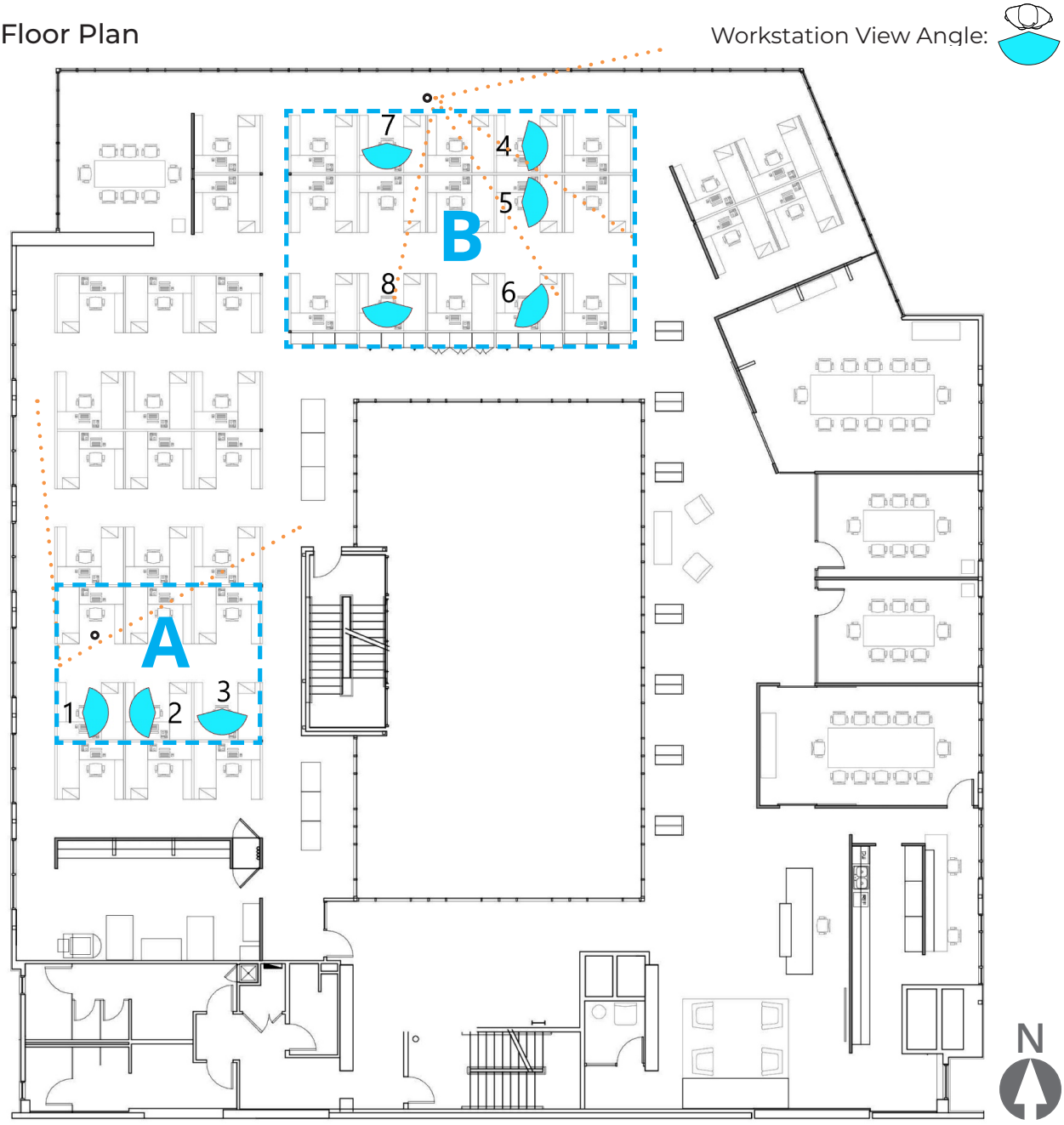




Case Study 2 - Weber Thompson Office

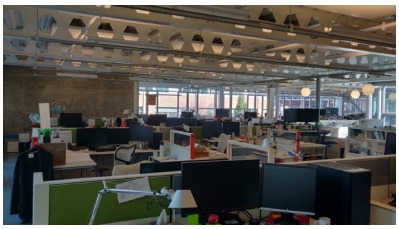
Floor Plan

Workstation View Angle:



Office Photos

ZONE A



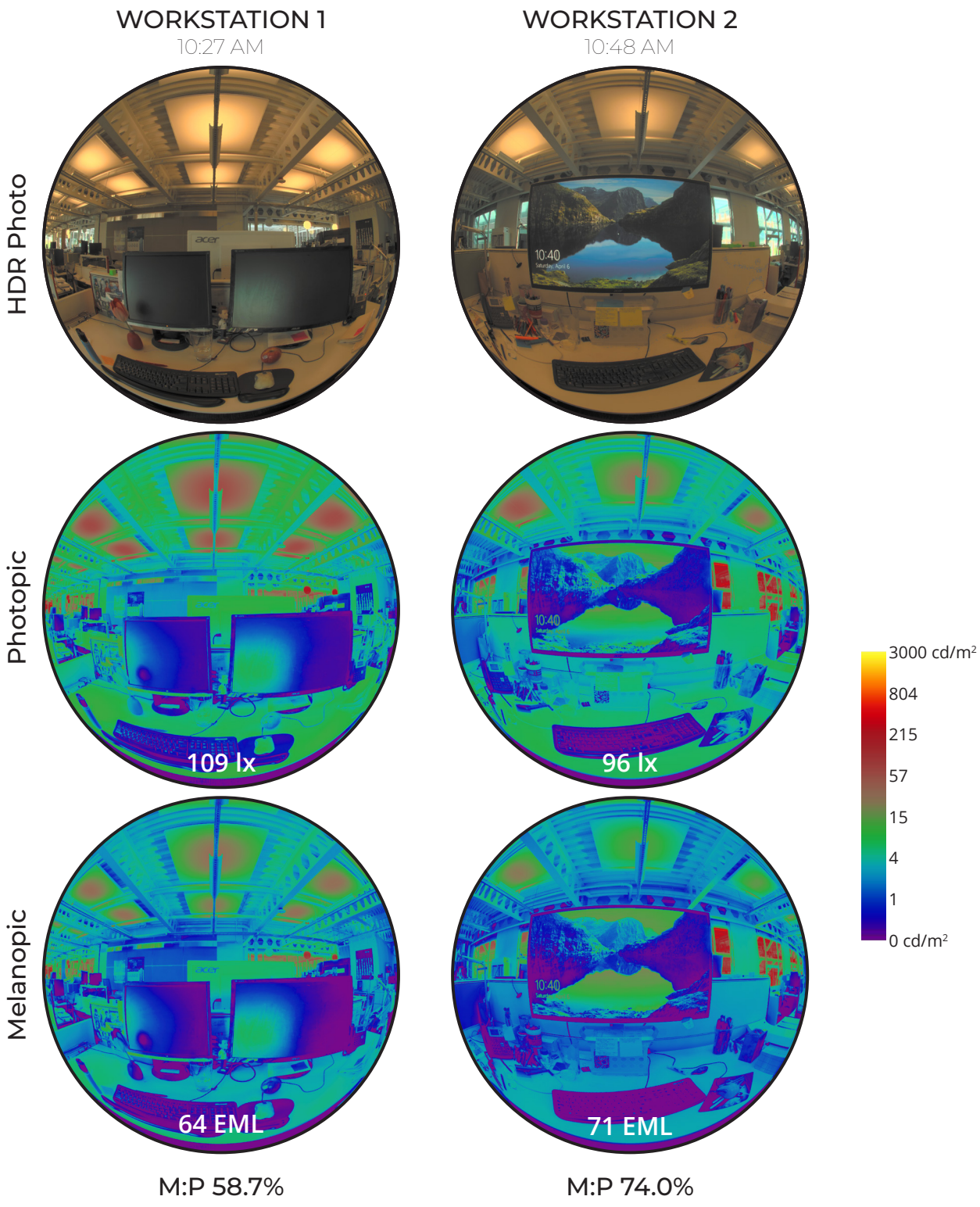
ZONE B





Study 2 - Zone A - All Lights On

Date: Sunday, April 6th
Weather: Partly Cloudy
Global Horizontal Solar Irradiance: 241 w/m²
Ambient Lighting Color Temp: 3500K

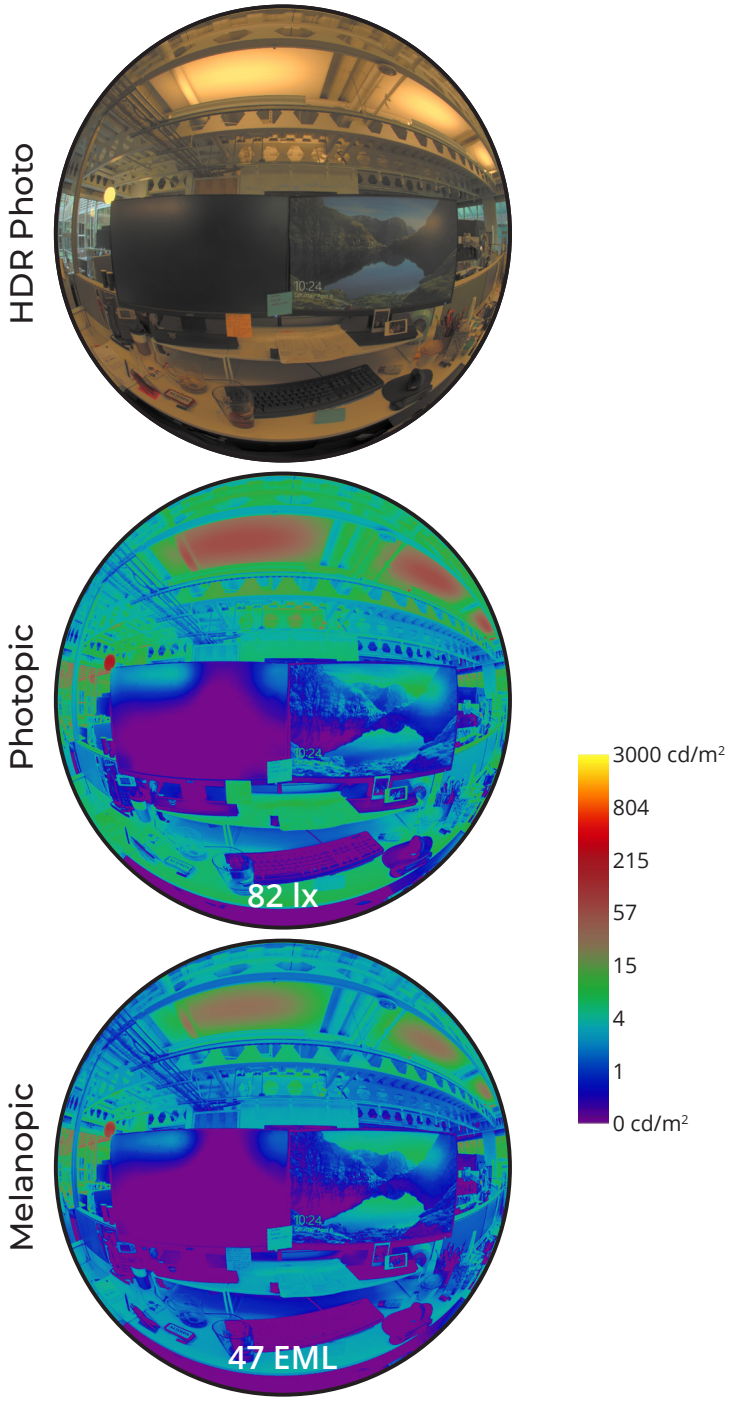


Study 2 - Zone A - All Lights On

Date: Sunday, April 6th
Weather: Partly Cloudy
Global Horizontal Solar Irradiance: 241 w/m²
Ambient Lighting Color Temp: 3500K

WORKSTATION 3

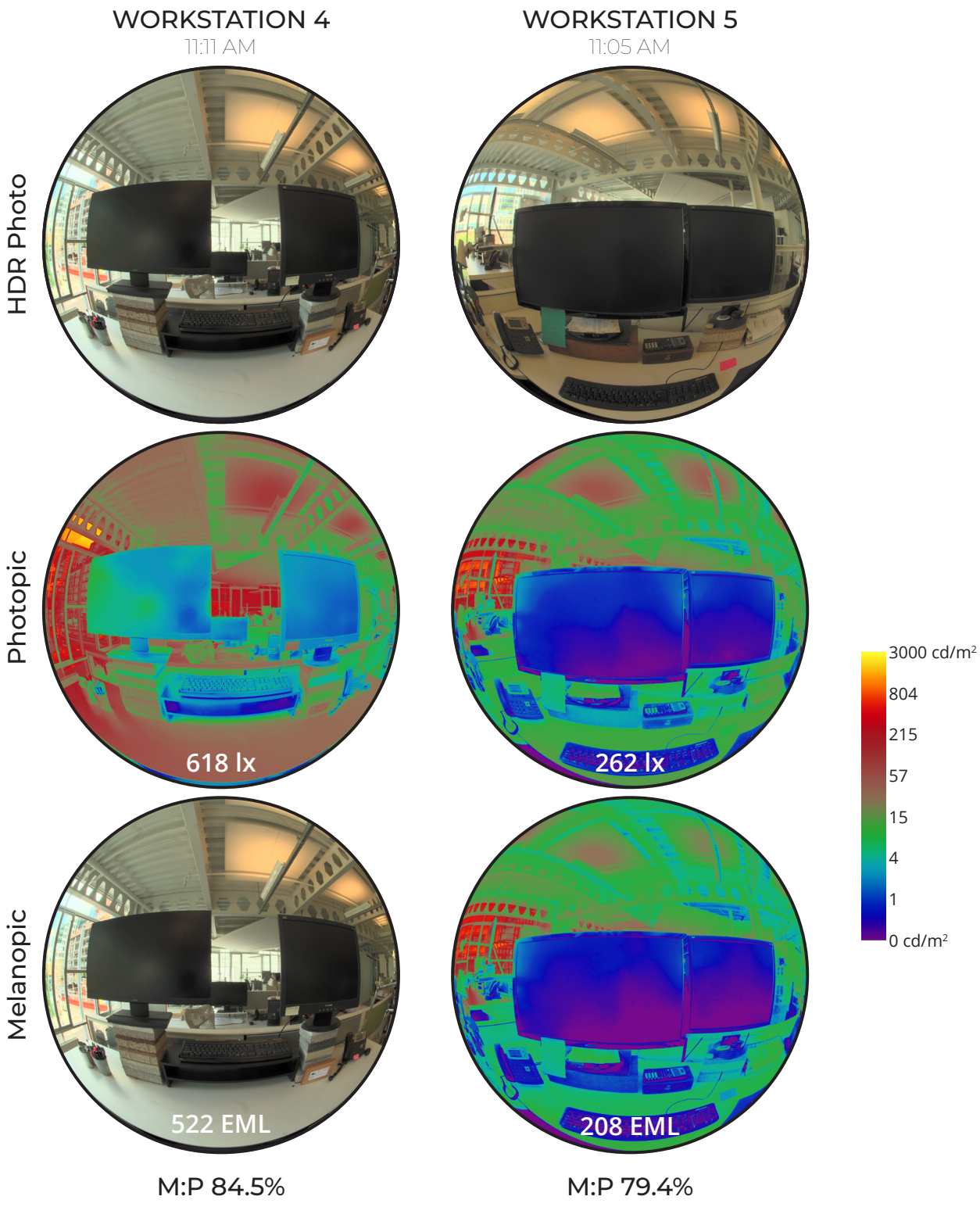
10:32 AM



M:P 57.3%

Study 2 - Zone B - All Lights On

Date: Sunday, April 6th
Weather: Partly Cloudy
Global Horizontal Solar Irradiance: 241 w/m²
Ambient Lighting Color Temp: 3500K

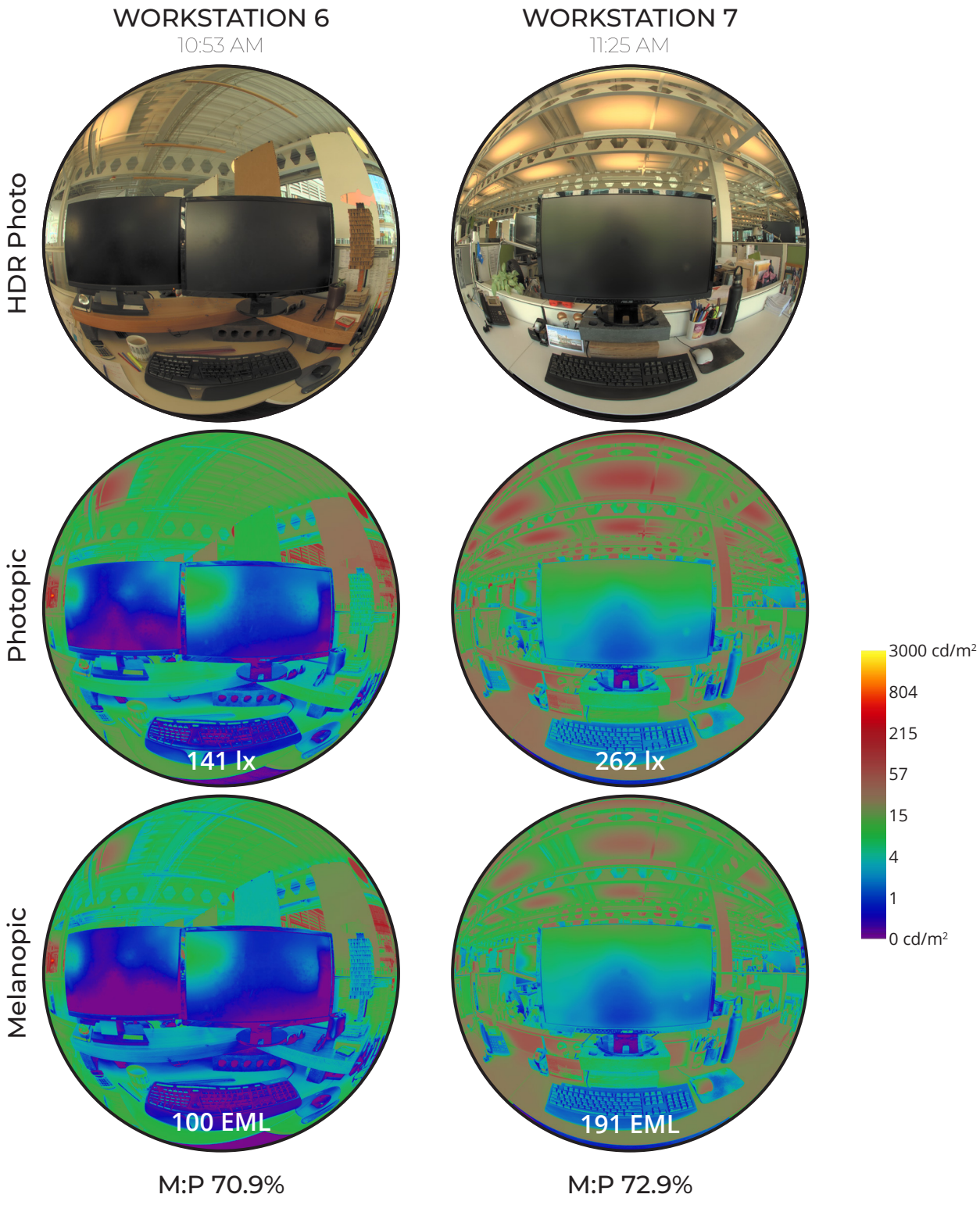


M:P 84.5%

M:P 79.4%

Study 2 - Zone B - All Lights On

Date: Sunday, April 6th
Weather: Partly Cloudy
Global Horizontal Solar Irradiance: 241 w/m²
Ambient Lighting Color Temp: 3500K



Study 2 - Zone B - All Lights On

Date: Sunday, April 6th
Weather: Partly Cloudy
Global Horizontal Solar Irradiance: 241 w/m²
Ambient Lighting Color Temp: 3500K

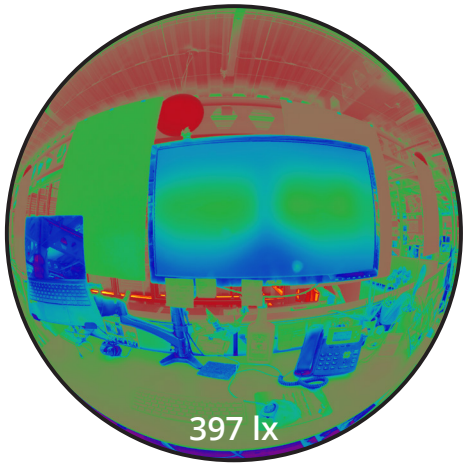
WORKSTATION 8

11:31 AM

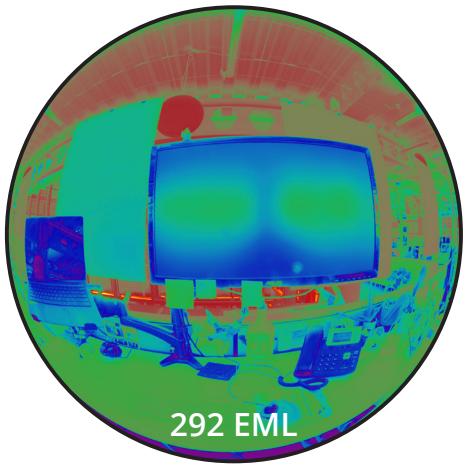
HDR Photo

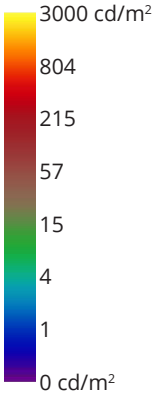


Photopic



Melanopic

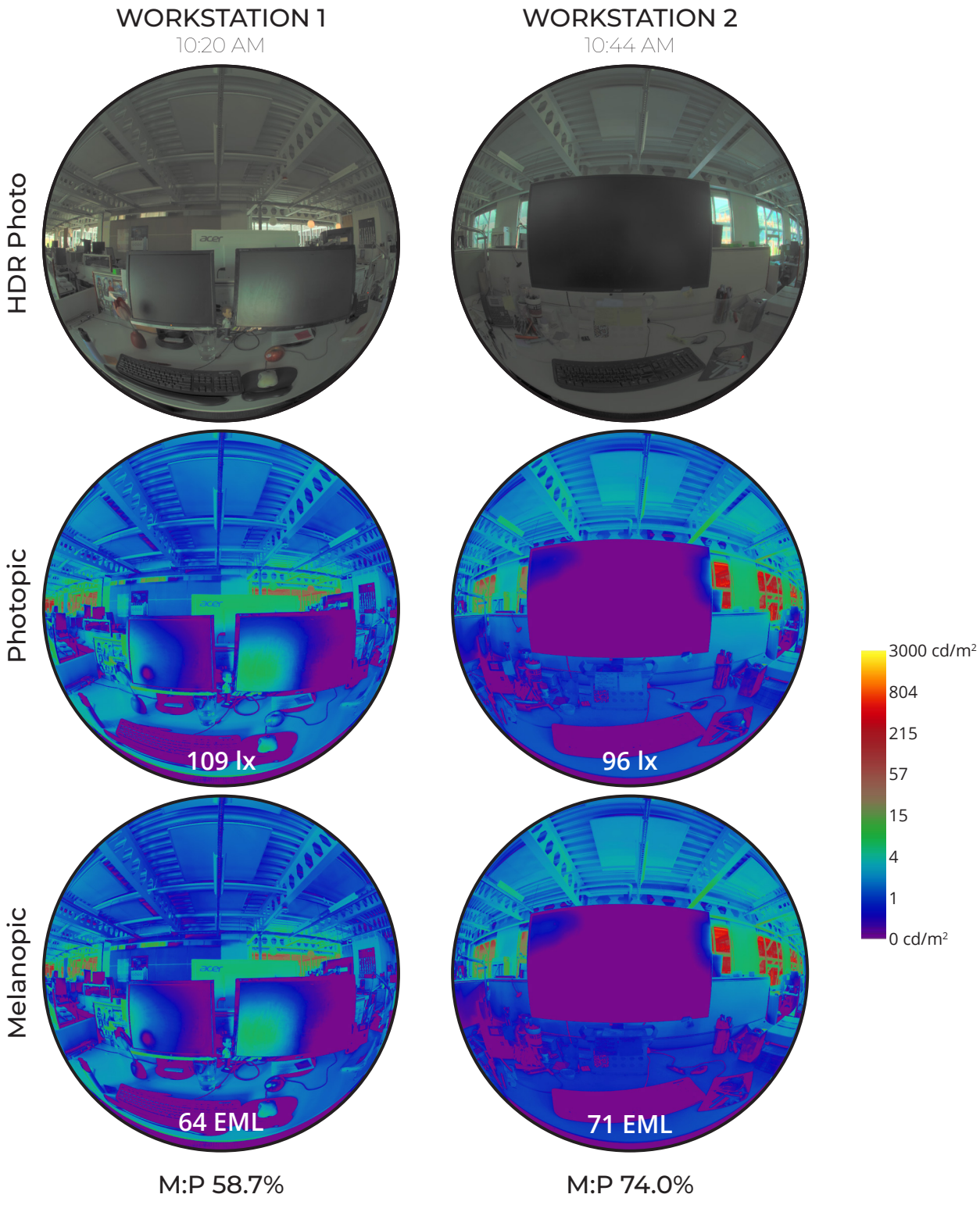




M:P 73.6%

Study 2 - Zone A - Daylight Only

Date: Sunday, April 6th
Weather: Partly Cloudy
Global Horizontal Solar Irradiance: 241 w/m²
Ambient Lighting Color Temp: 3500K



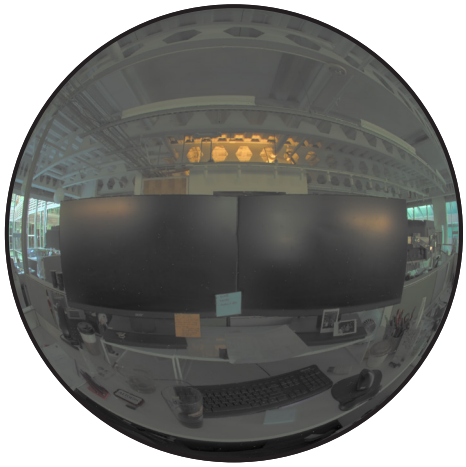
Study 2 - Zone A - Daylight Only

Date: Sunday, April 6th
Weather: Partly Cloudy
Global Horizontal Solar Irradiance: 241 w/m²
Ambient Lighting Color Temp: 3500K

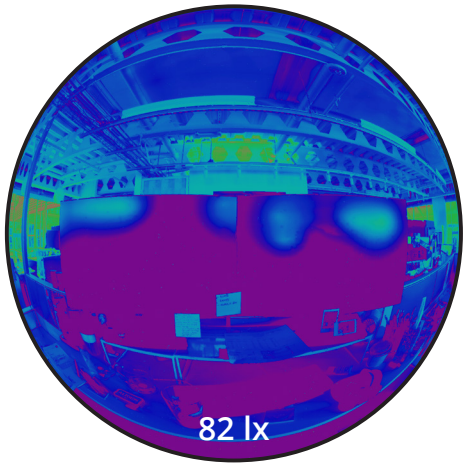
WORKSTATION 3

10:36 AM

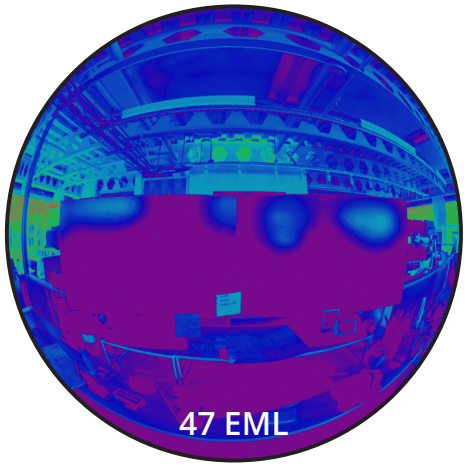
HDR Photo

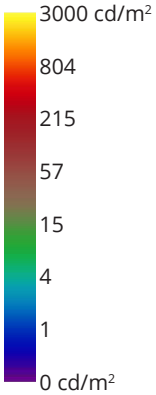


Photopic



Melanopic

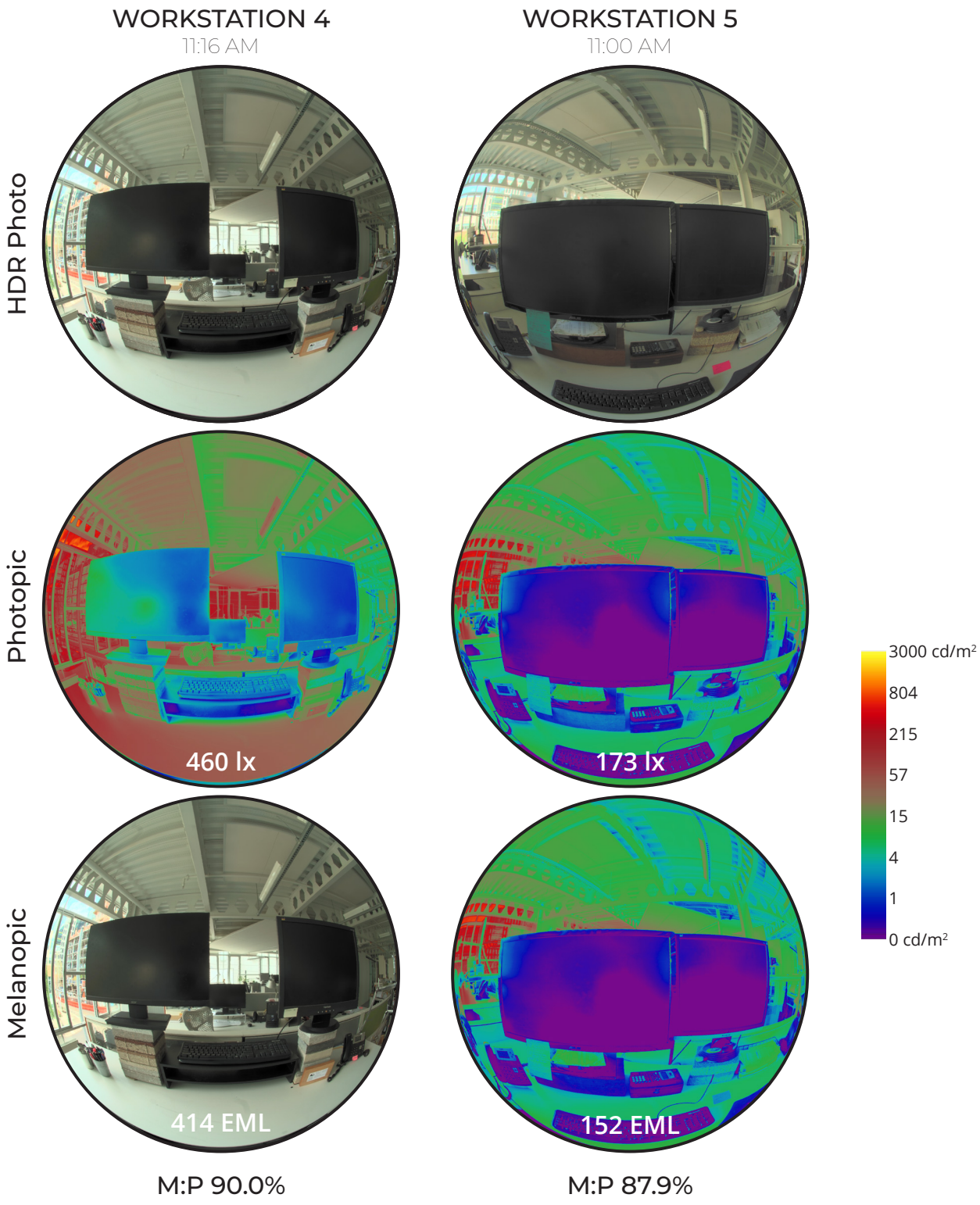




M:P 57.3%

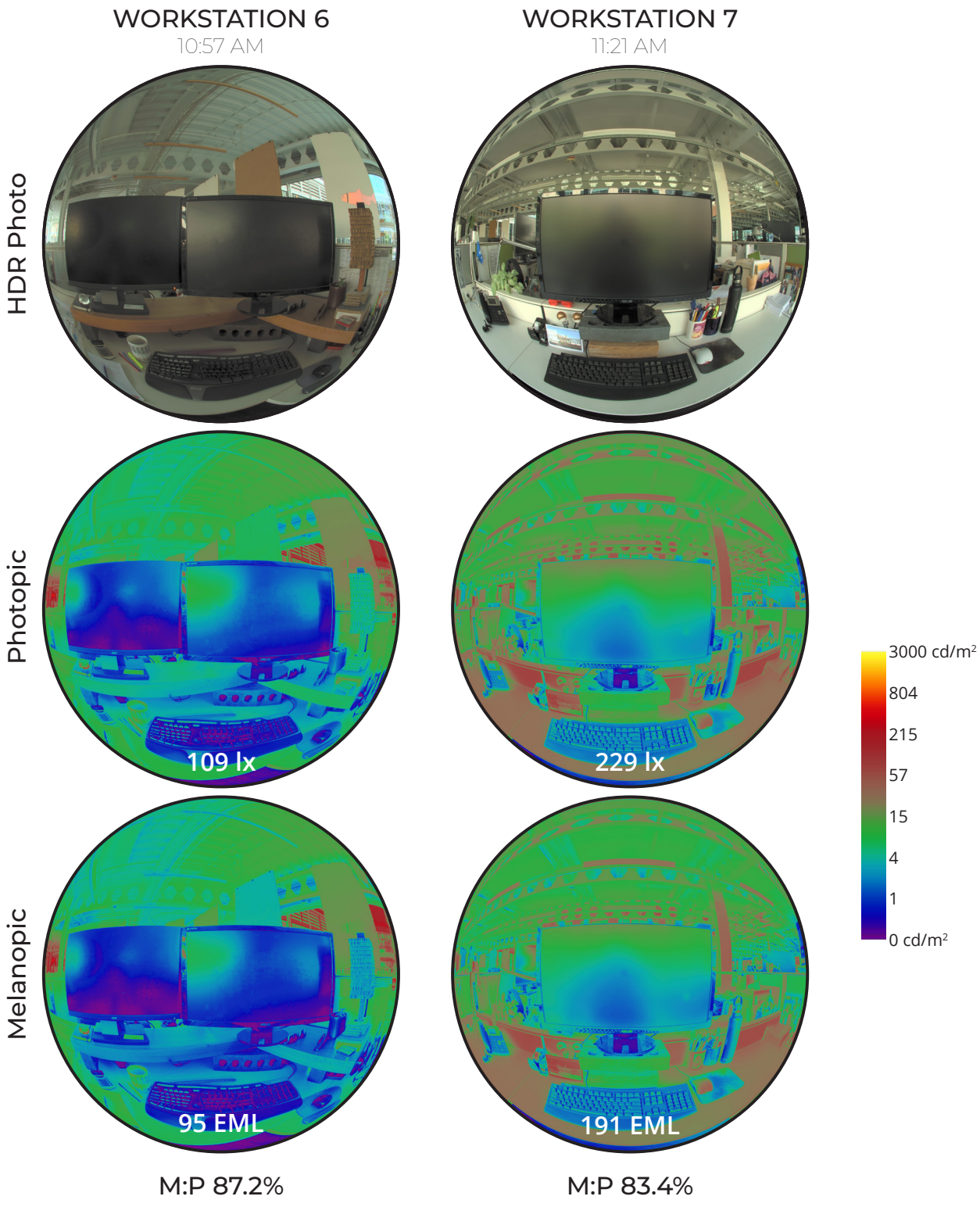
Study 2 - Zone B - Daylight Only

Date: Sunday, April 6th
Weather: Partly Cloudy
Global Horizontal Solar Irradiance: 241 w/m²
Ambient Lighting Color Temp: 3500K



Study 2 - Zone B - Daylight Only

Date: Sunday, April 6th
Weather: Partly Cloudy
Global Horizontal Solar Irradiance: 241 w/m²
Ambient Lighting Color Temp: 3500K



Study 2 - Zone B - Daylight Only

Date: Sunday, April 6th
Weather: Partly Cloudy
Global Horizontal Solar Irradiance: 241 w/m²
Ambient Lighting Color Temp: 3500K

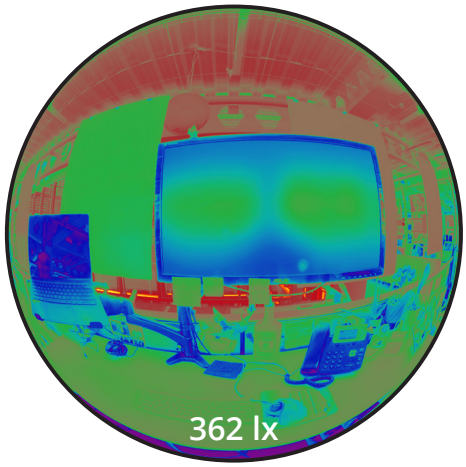
WORKSTATION 8

11:34 AM

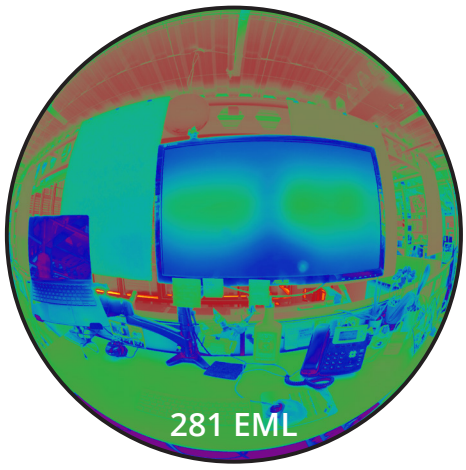
HDR Photo

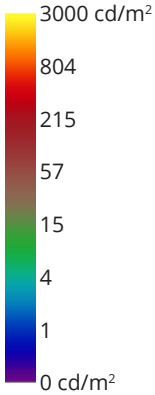


Photopic



Melanopic

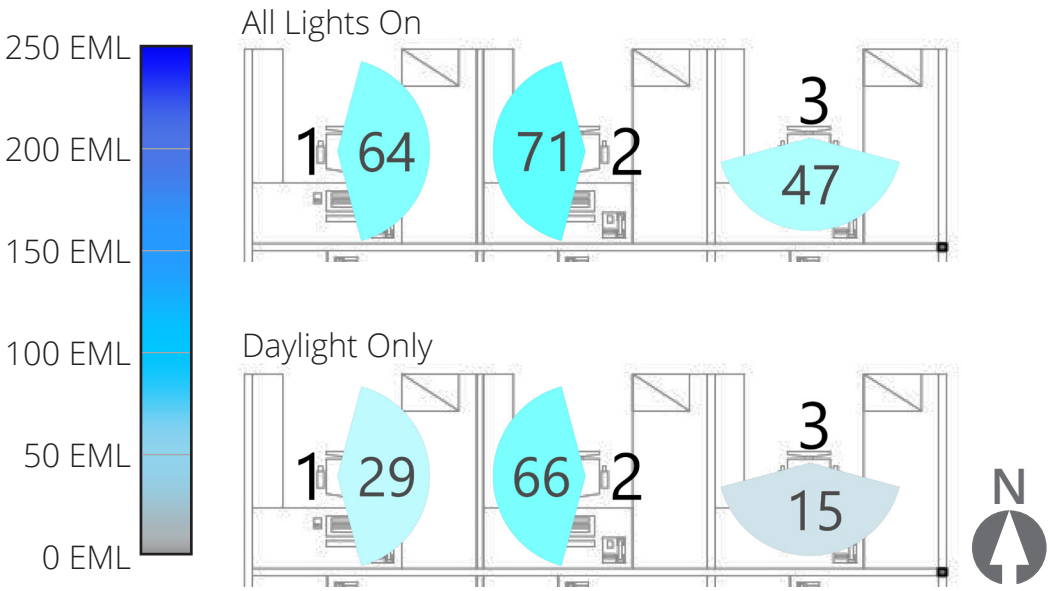


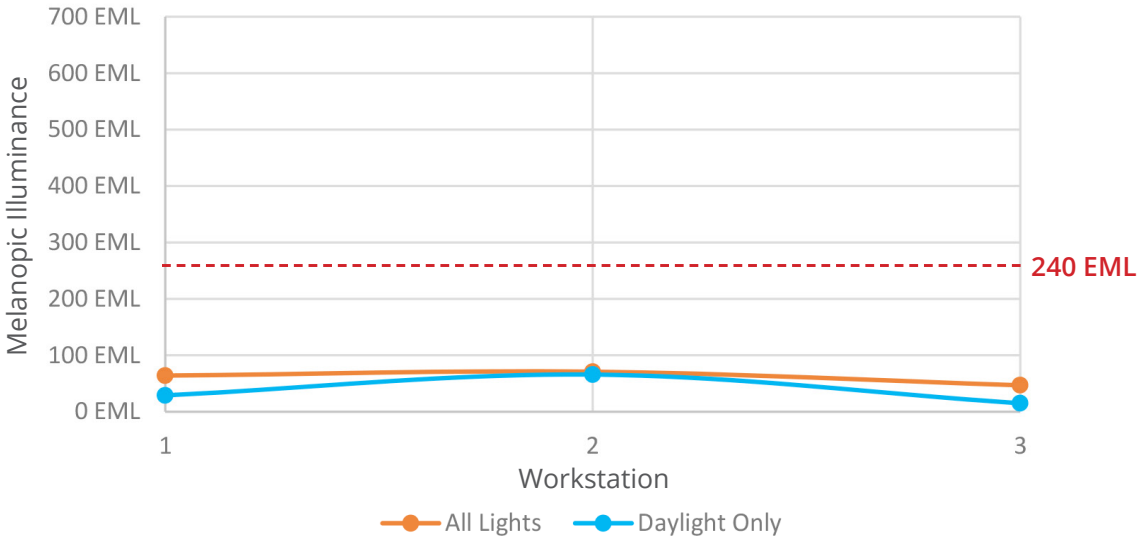


M:P 77.6%

Study 2 - Zone A - Melanopic Illuminance

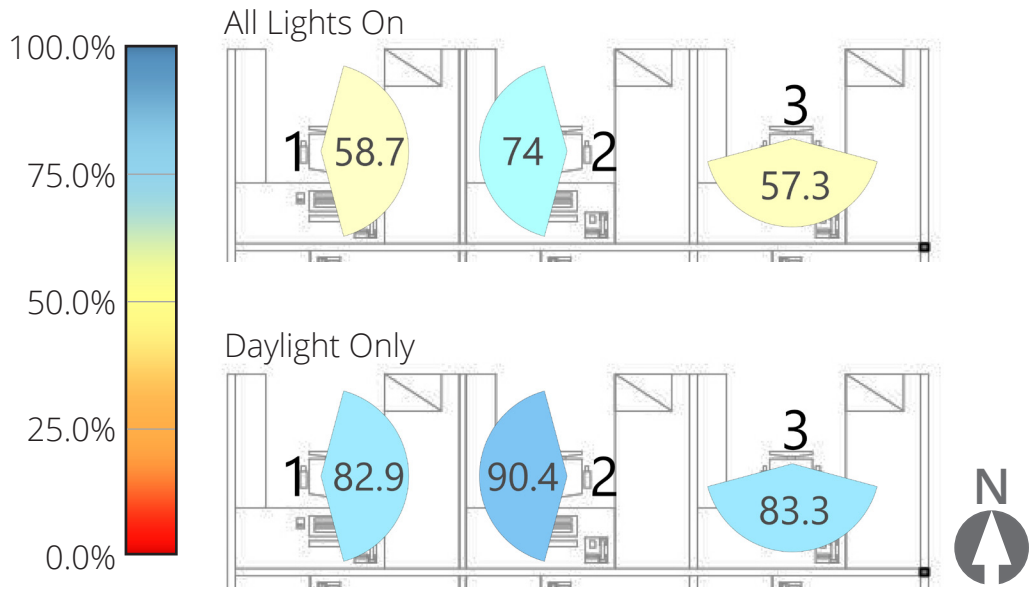
Date: Sunday, April 6th
Weather: Partly Cloudy
Global Horizontal Solar Irradiance: 241 w/m²
Ambient Lighting Color Temp: 3500K

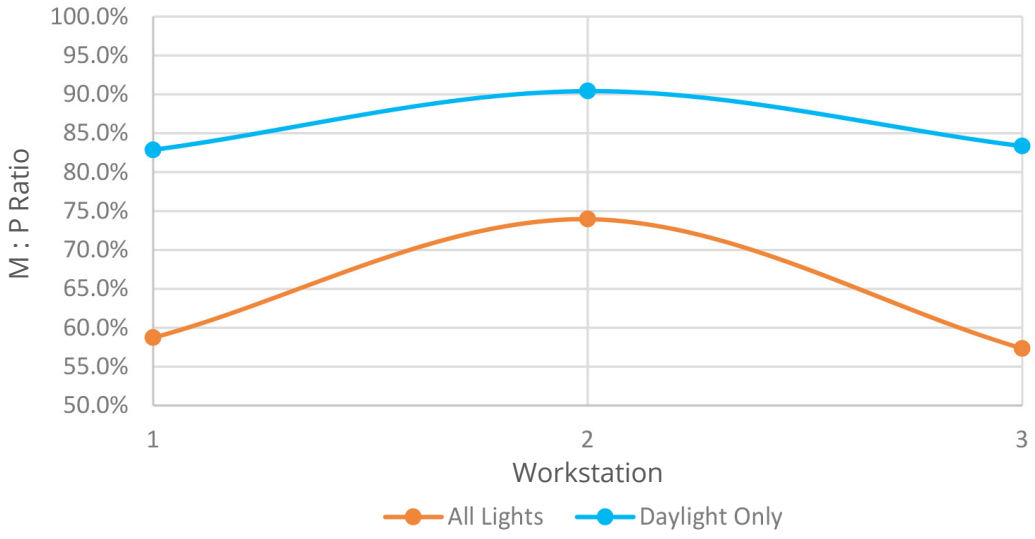




Study 2 - Zone A - Melanopic : Photopic Ratio

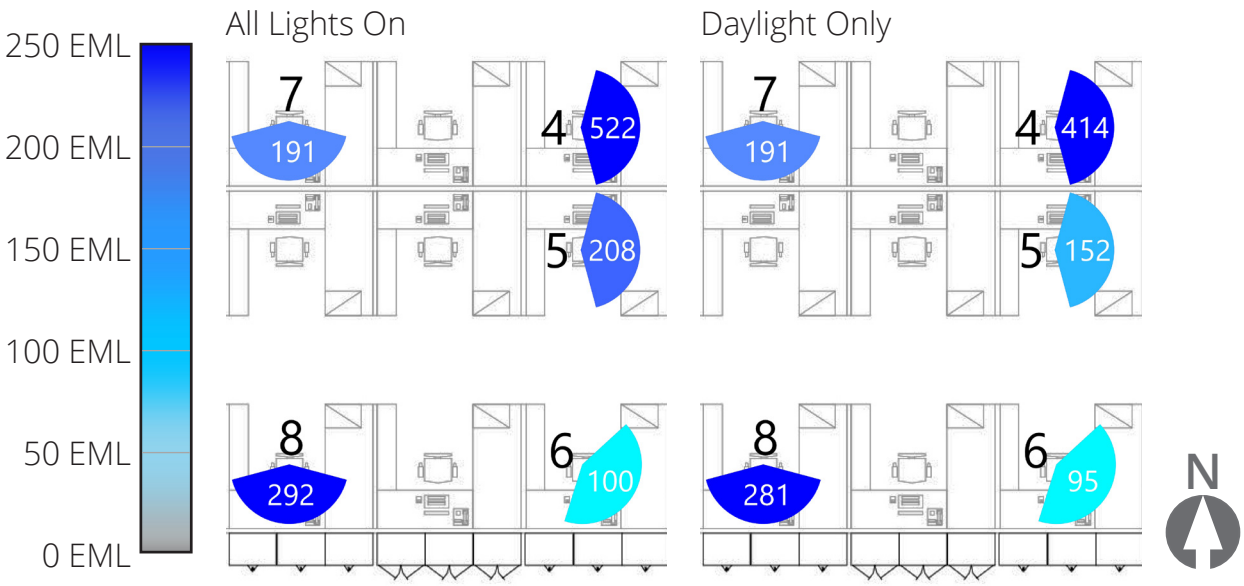
Date: Sunday, April 6th
Weather: Partly Cloudy
Global Horizontal Solar Irradiance: 241 w/m²
Ambient Lighting Color Temp: 3500K

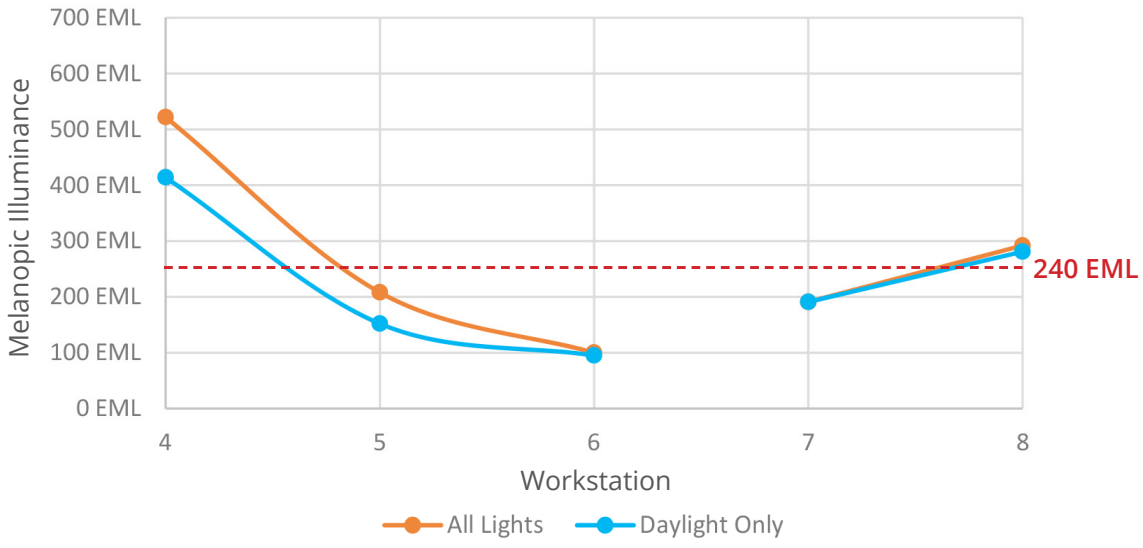




Study 2 - Zone B - Melanopic Illuminance

Date: Sunday, April 6th
Weather: Partly Cloudy
Global Horizontal Solar Irradiance: 241 w/m²
Ambient Lighting Color Temp: 3500K

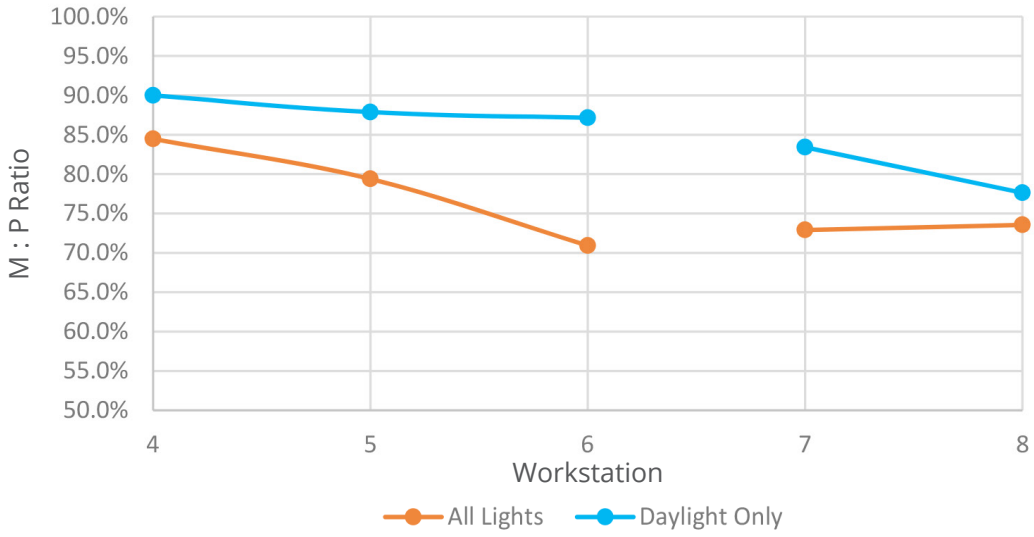




Study 2 - Zone B - Melanopic : Photopic Ratio

Date: Sunday, April 6th
Weather: Partly Cloudy
Global Horizontal Solar Irradiance: 241 w/m²
Ambient Lighting Color Temp: 3500K





Case Study 3 - UW Tower

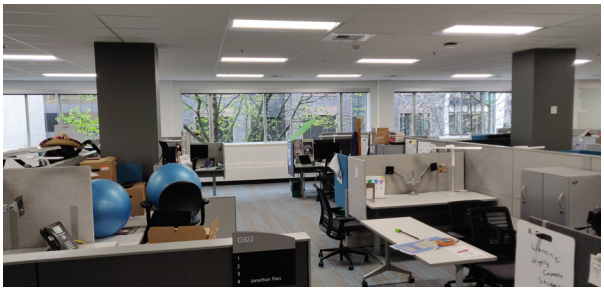
Study 3.1 - Level O-3 Floor Plan

Workstation View Angle: 



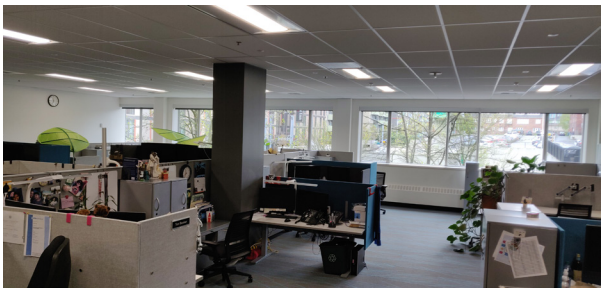
Office Photos

ZONE A



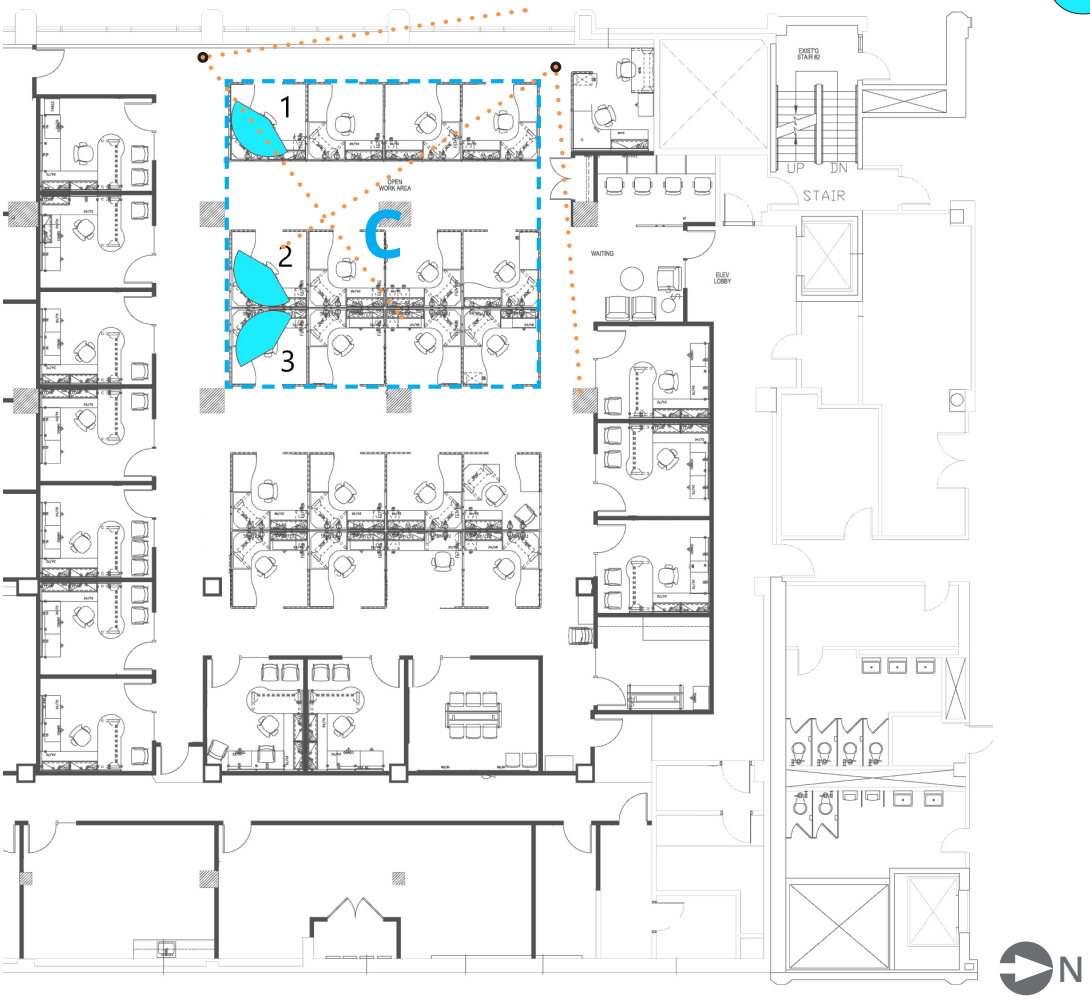


ZONE B



Study 3.2 - Level C-1 Floor Plan

Workstation View Angle:



Office Photos

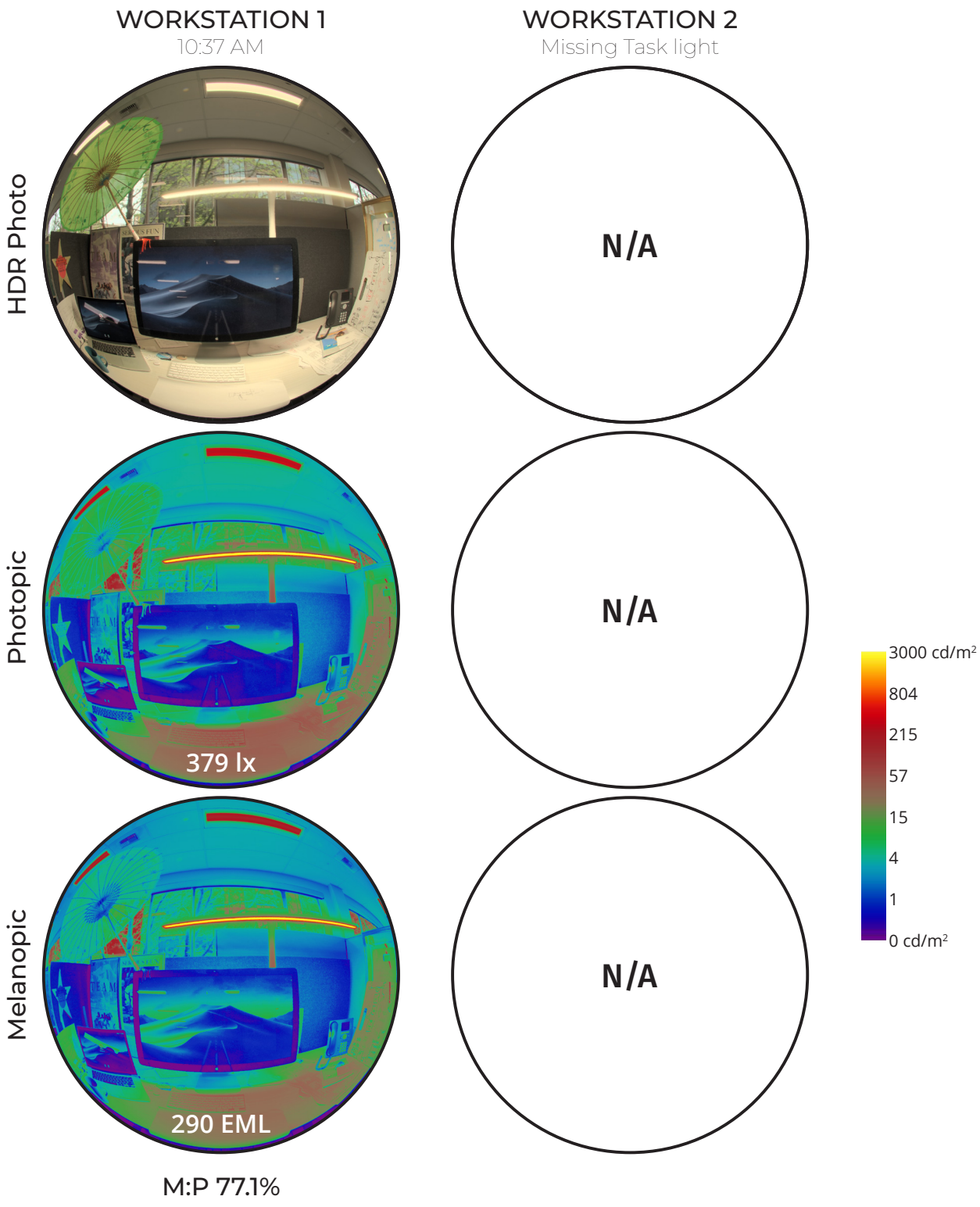
ZONE C





Study 3.1 - Level O-3 - Zone A - All Lights On

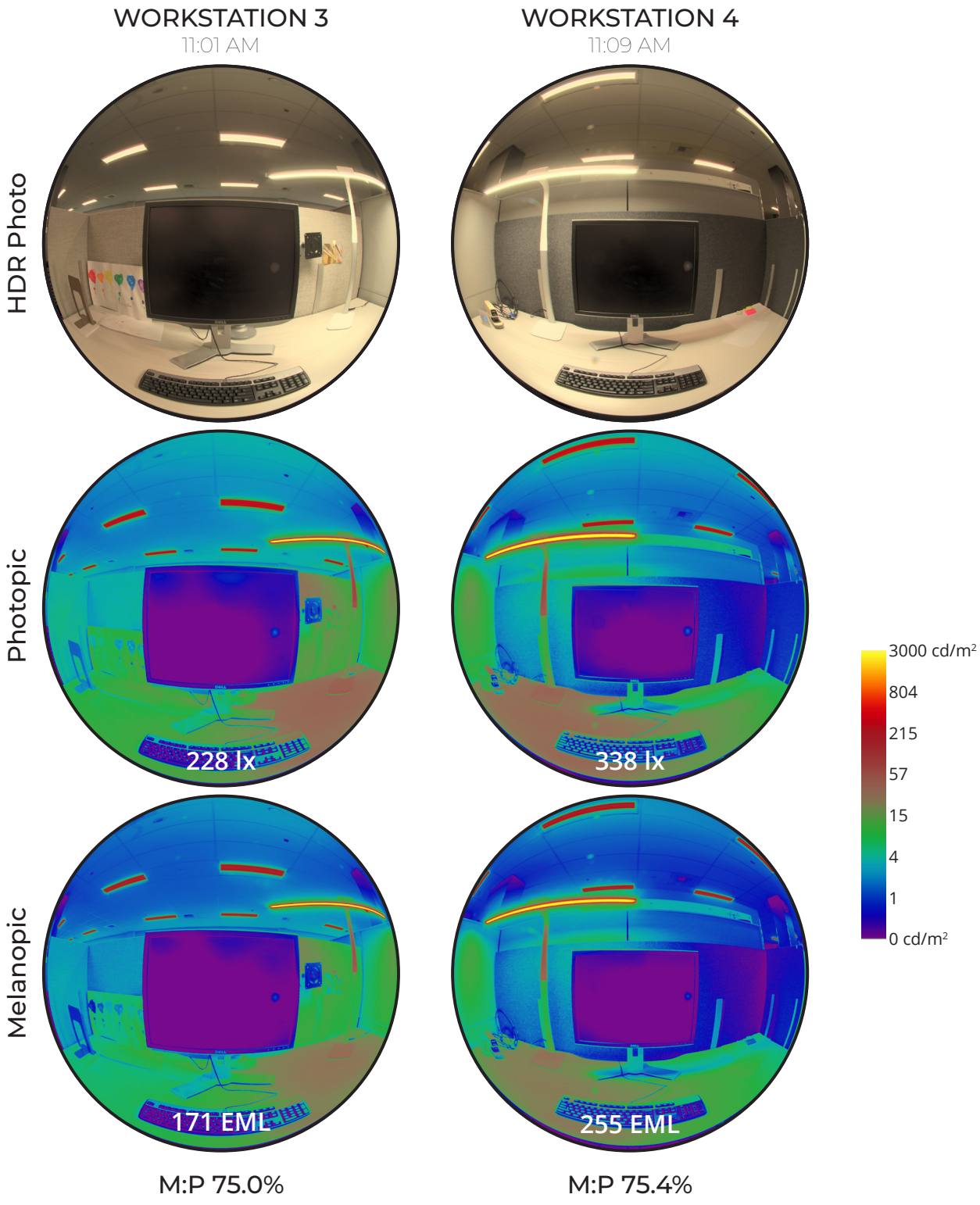
Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K



M:P 77.1%

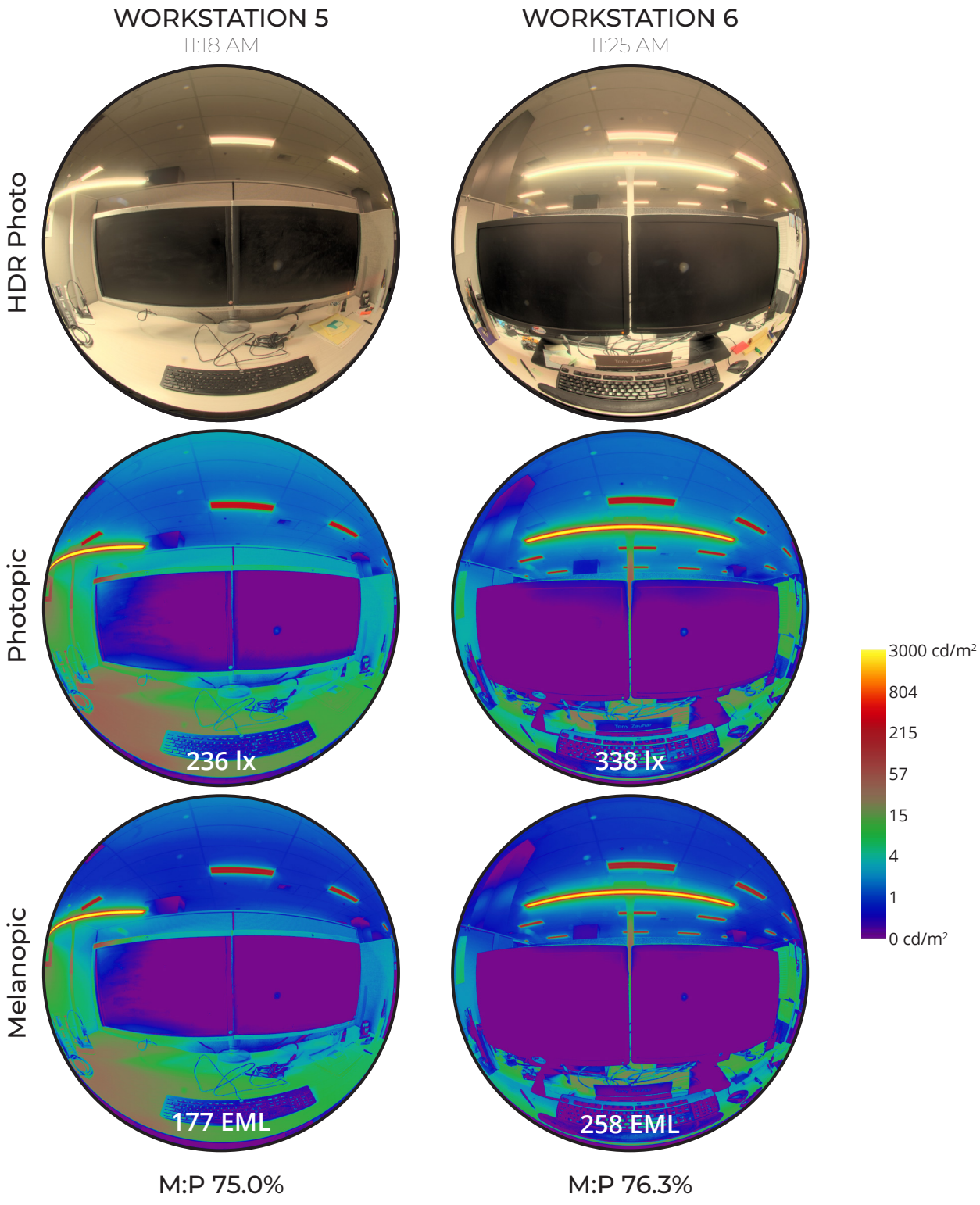
Study 3.1 - Level O-3 - Zone A - All Lights On

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K



Study 3.1 - Level O-3 - Zone A - All Lights On

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K



Study 3.1 - Level O-3 - Zone A - All Lights On

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K

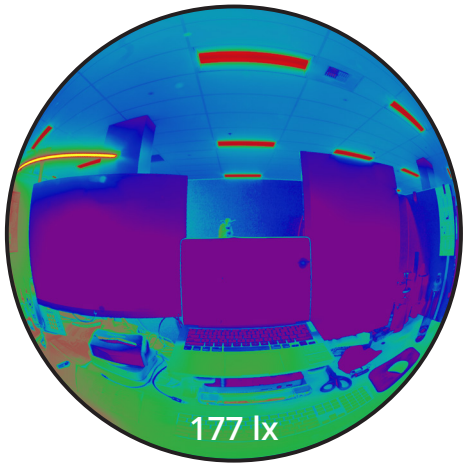
WORKSTATION 7

11:32 AM

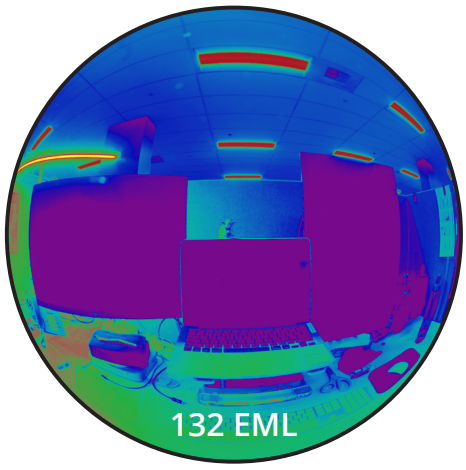
HDR Photo

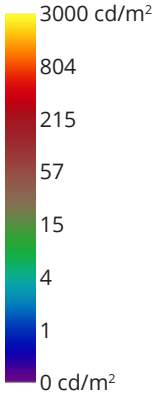


Photopic



Melanopic

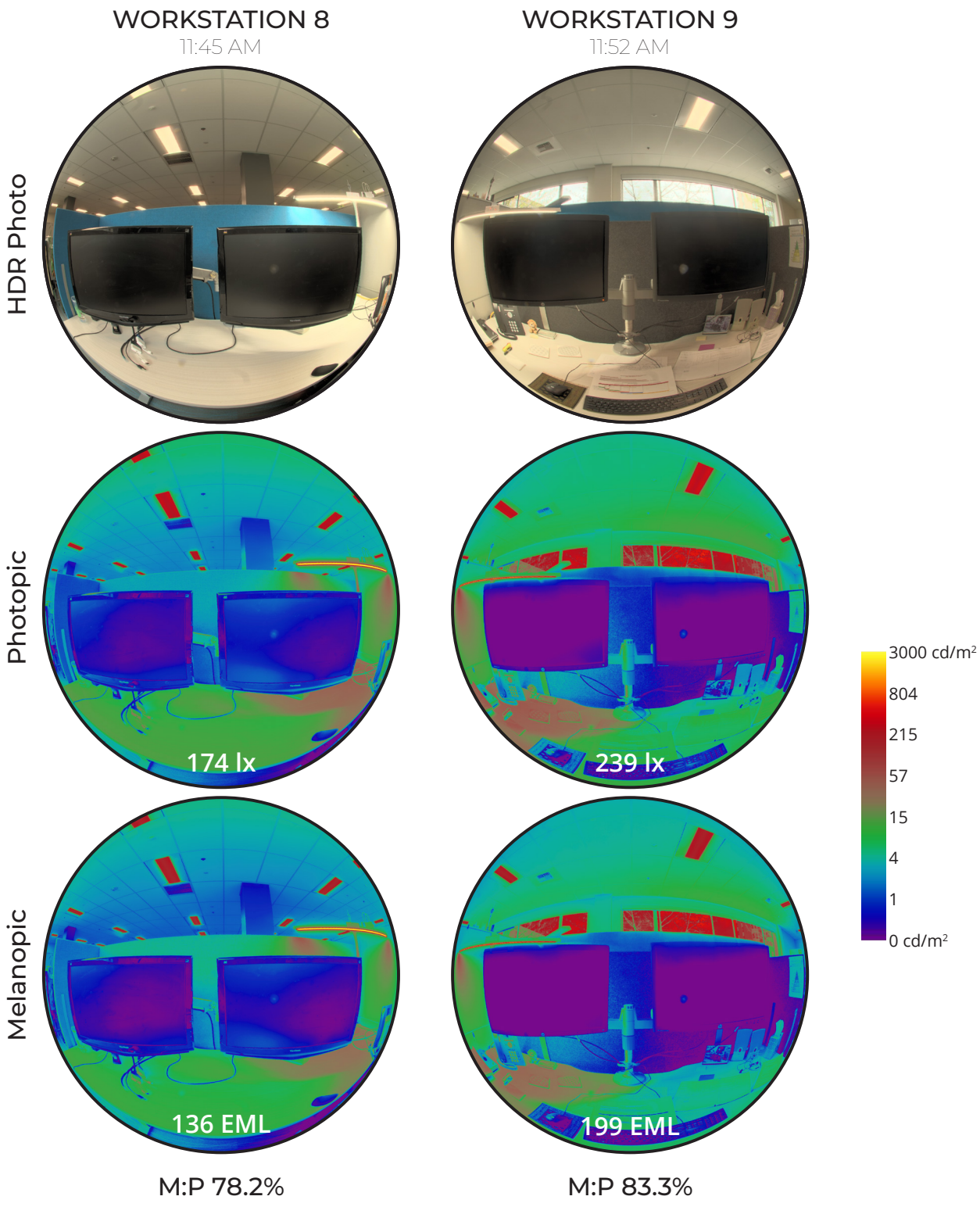




M:P 74.6%

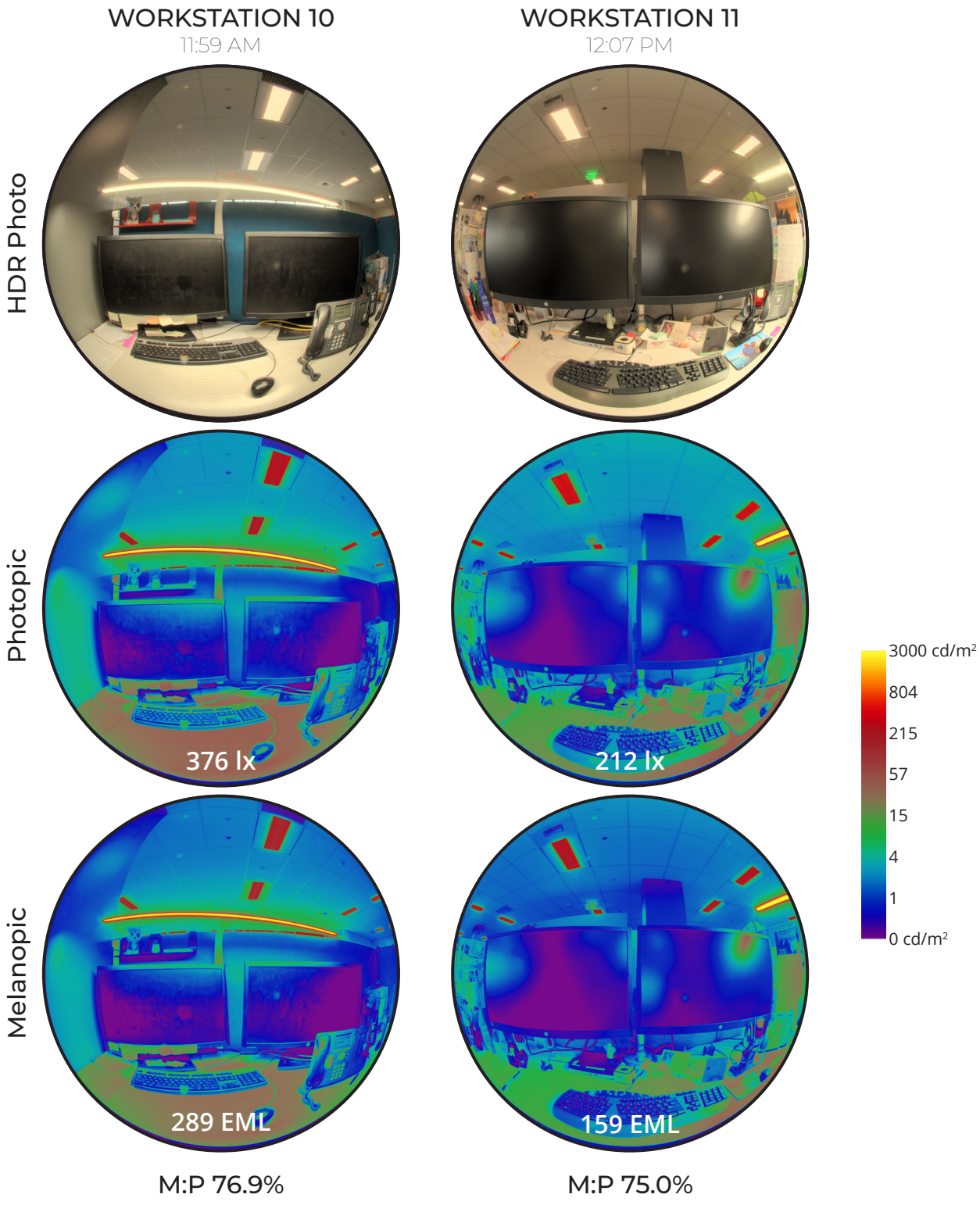
Study 3.1 - Level O-3 - Zone B - All Lights On

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K



Study 3.1 - Level O-3 - Zone B - All Lights On

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K

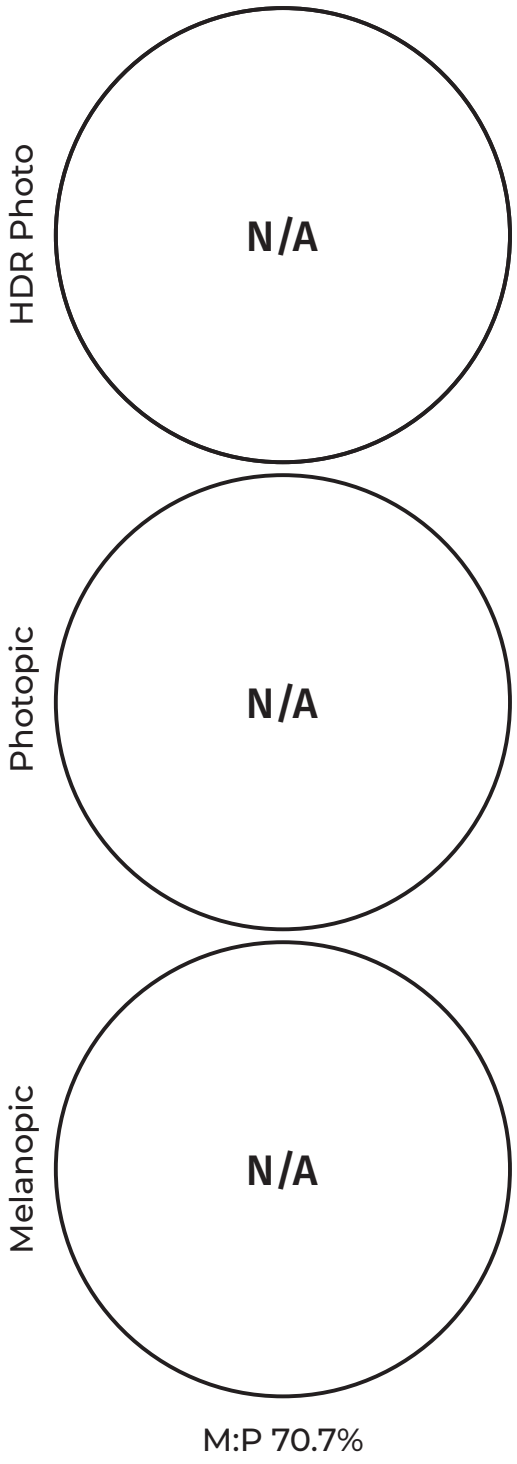


Study 3.1 - Level O-3 - Zone B - All Lights On

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K

WORKSTATION 12

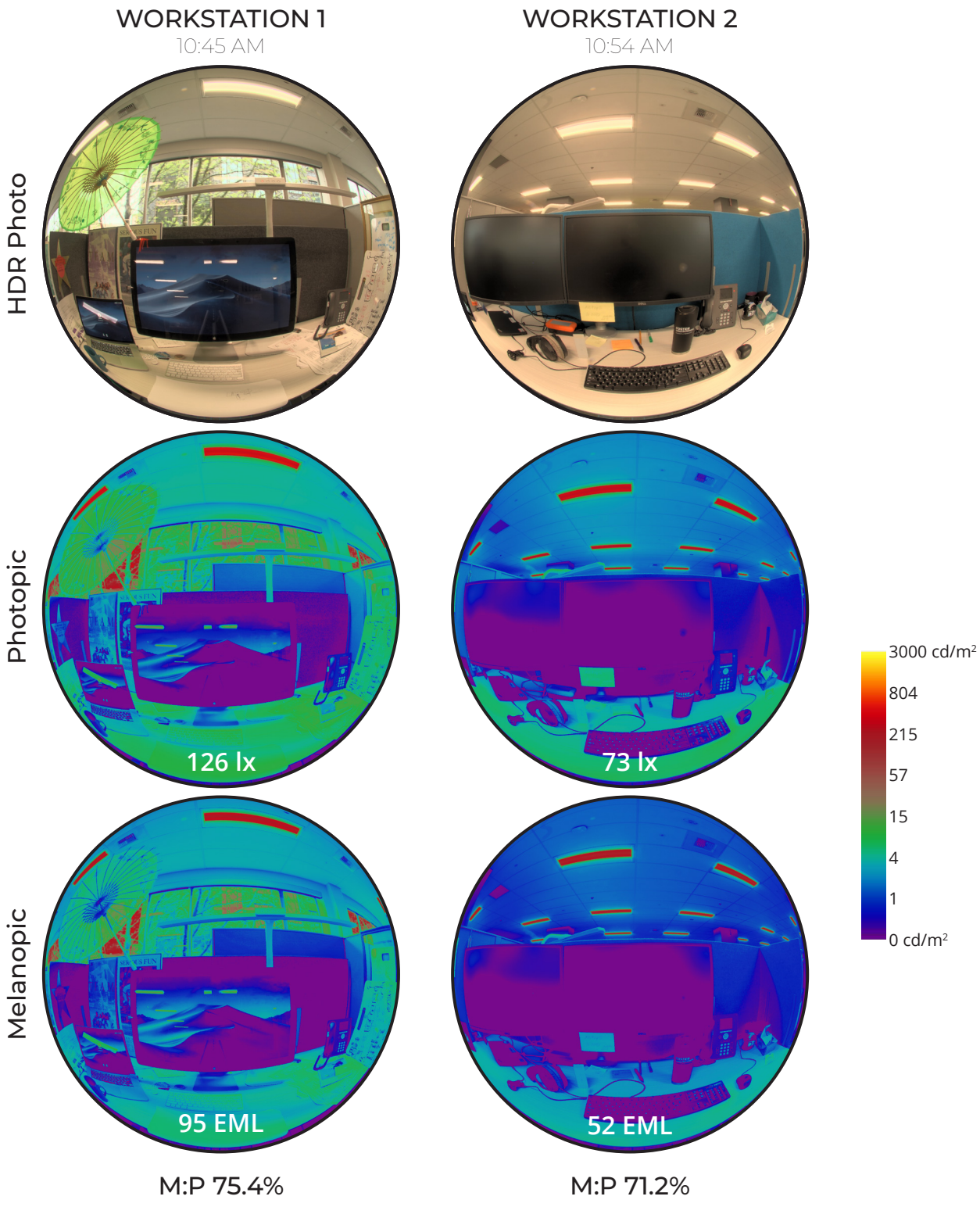
Missing Task Light



M:P 70.7%

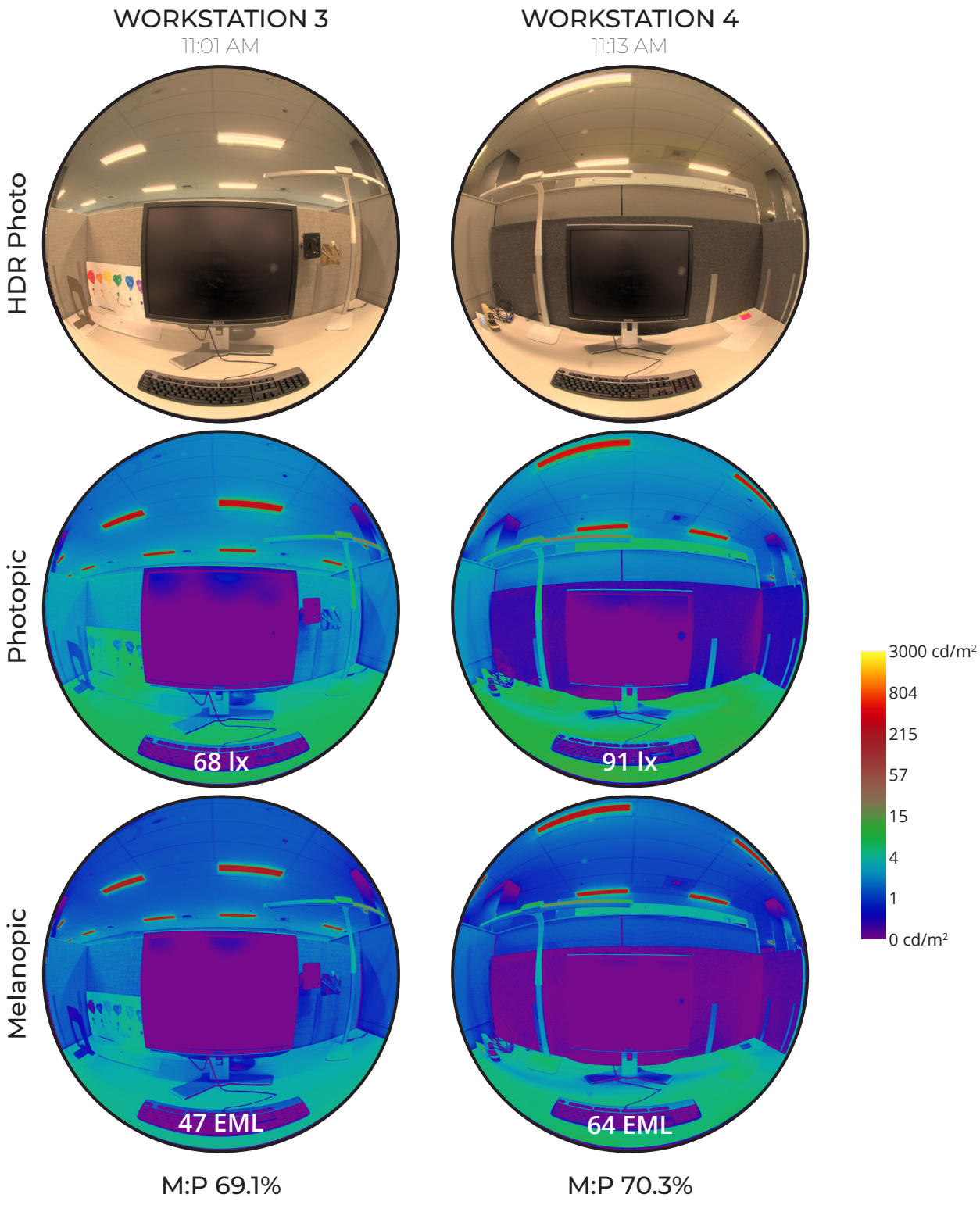
Study 3.1 - Level O-3 - Zone A - No Task Light

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K



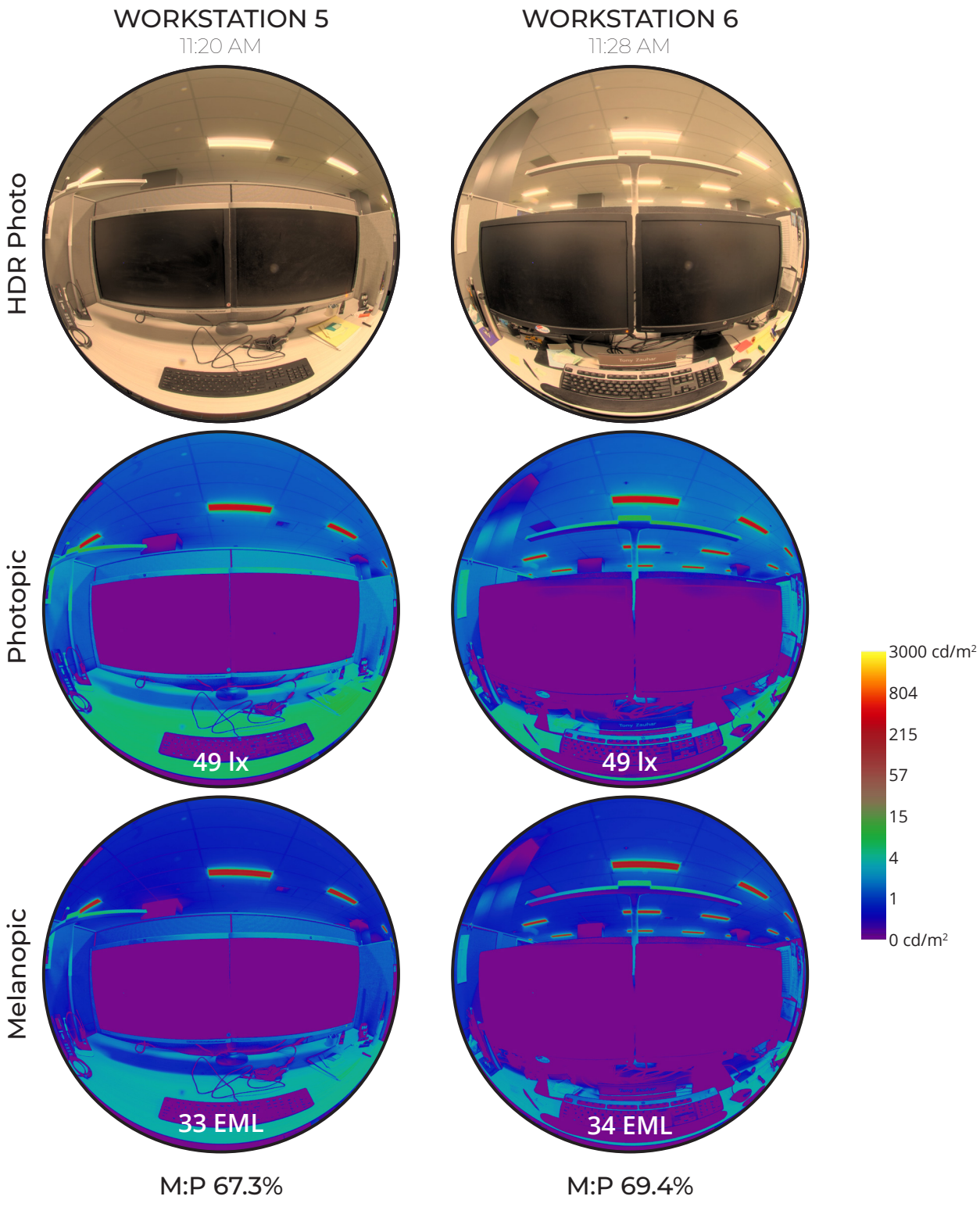
Study 3.1 - Level O-3 - Zone A - No Task Light

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K



Study 3.1 - Level O-3 - Zone A - No Task Light

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K



M:P 67.3%

M:P 69.4%

Study 3.1 - Level O-3 - Zone A - No Task Light

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K

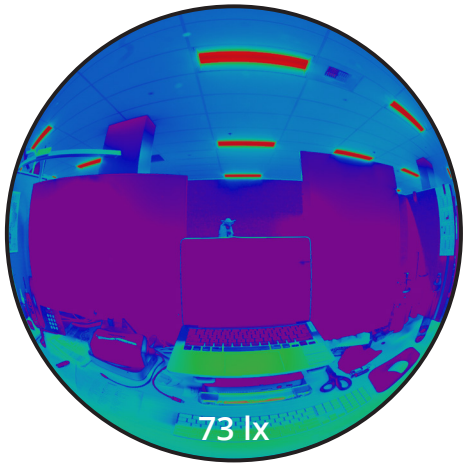
WORKSTATION 7

10:42 AM

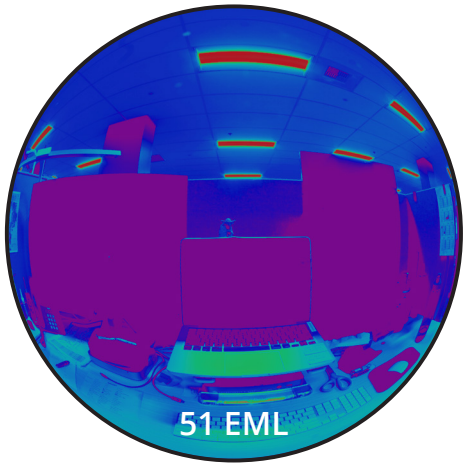
HDR Photo

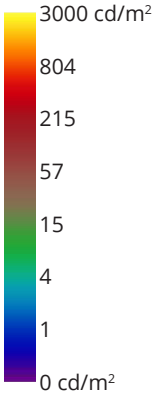


Photopic



Melanopic

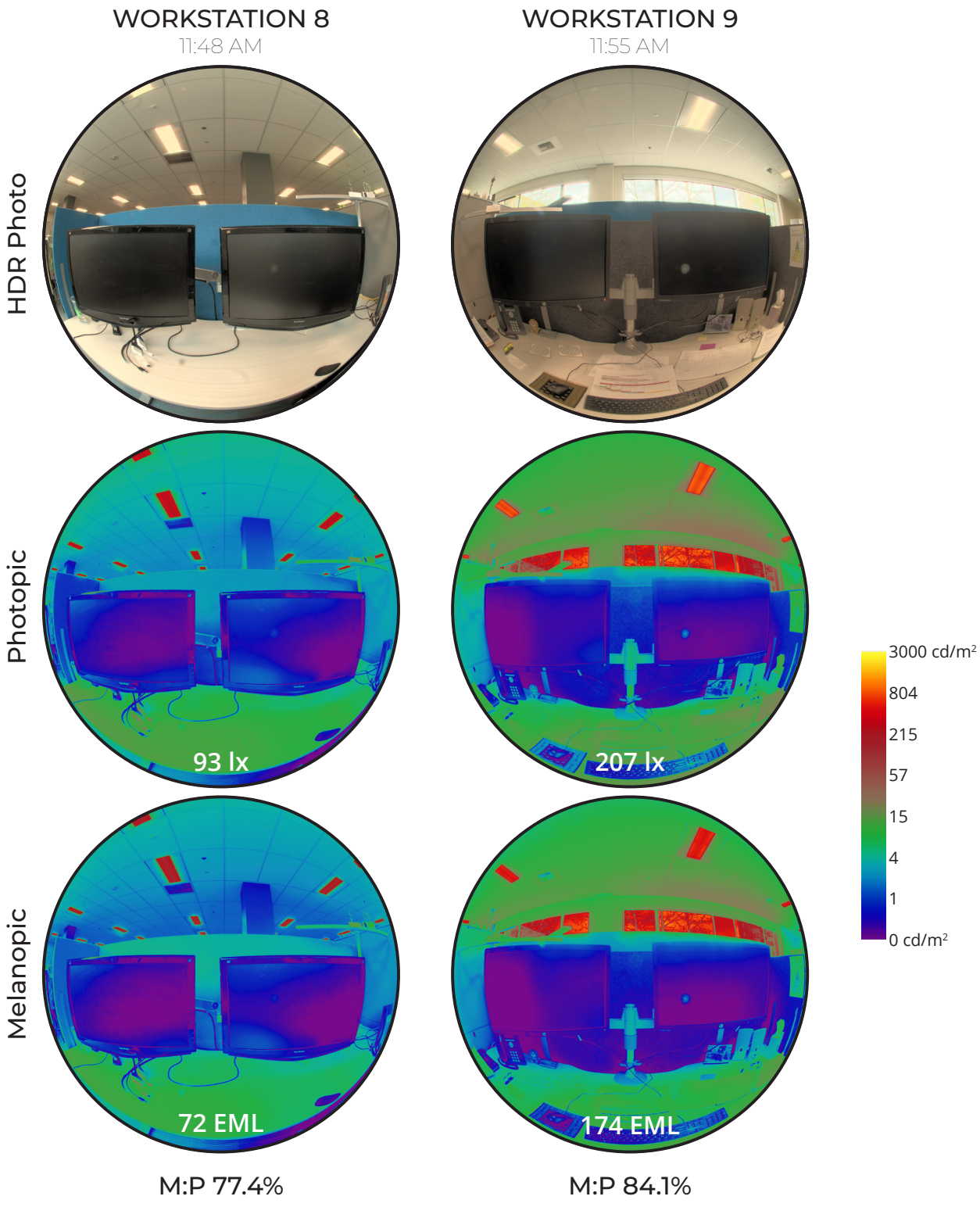




M:P 69.9%

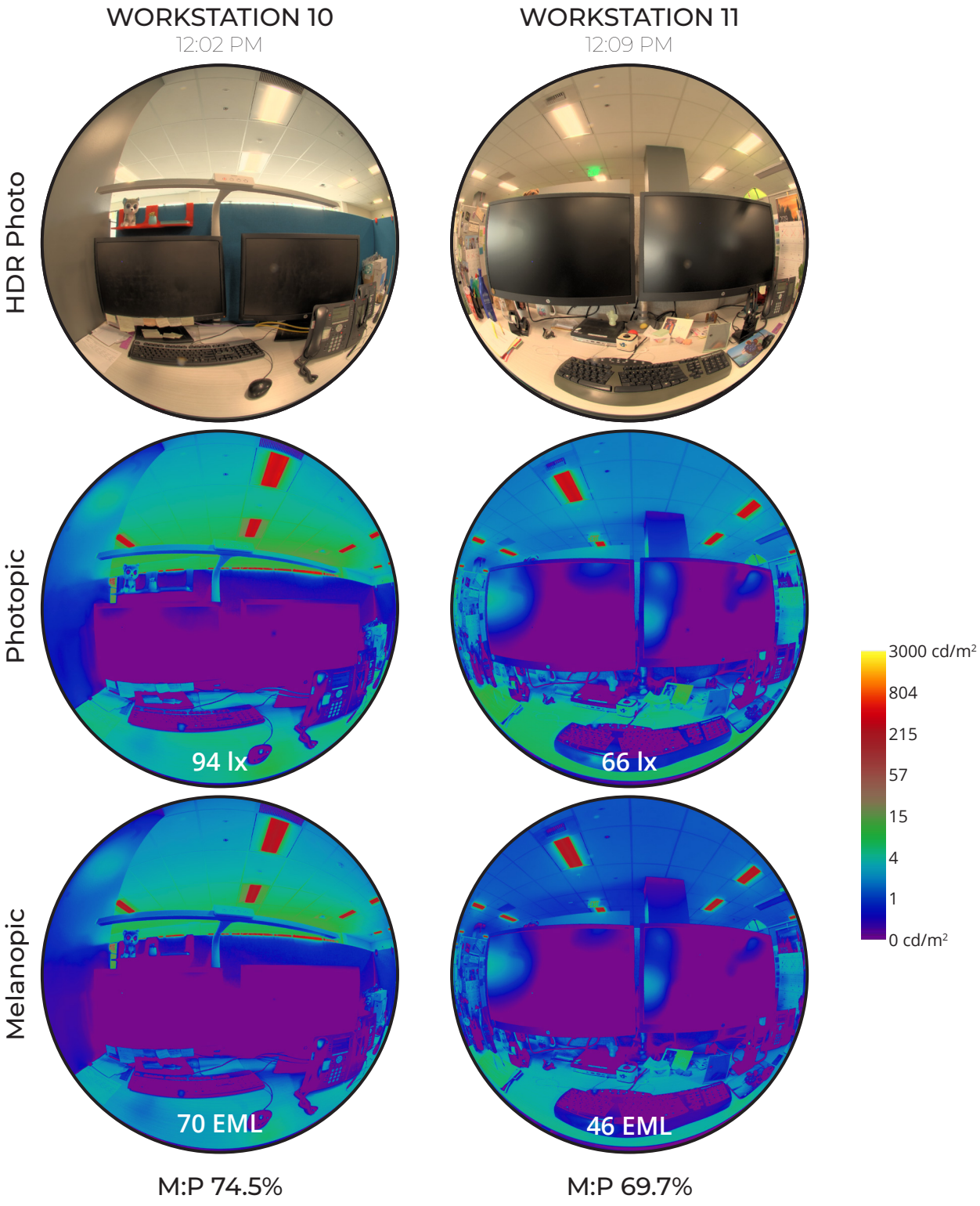
Study 3.1 - Level O-3 - Zone B - No Task Light

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K



Study 3.1 - Level O-3 - Zone B - No Task Light

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K



Study 3.1 - Level O-3 - Zone B - No Task Light

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K

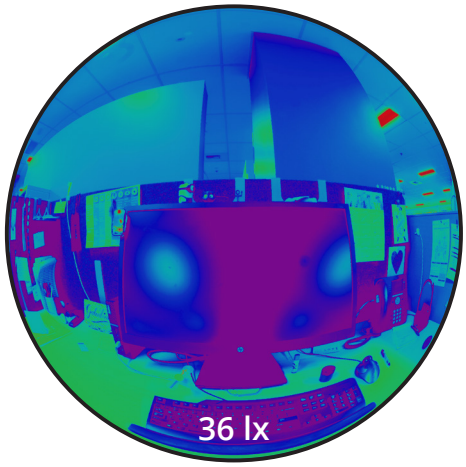
WORKSTATION 12

12:13 PM

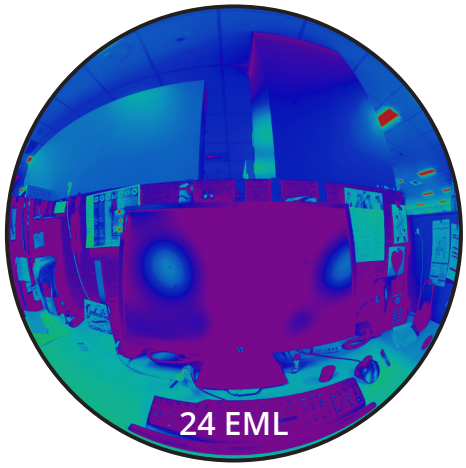
HDR Photo

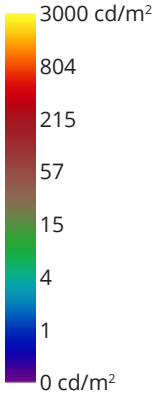


Photopic



Melanopic

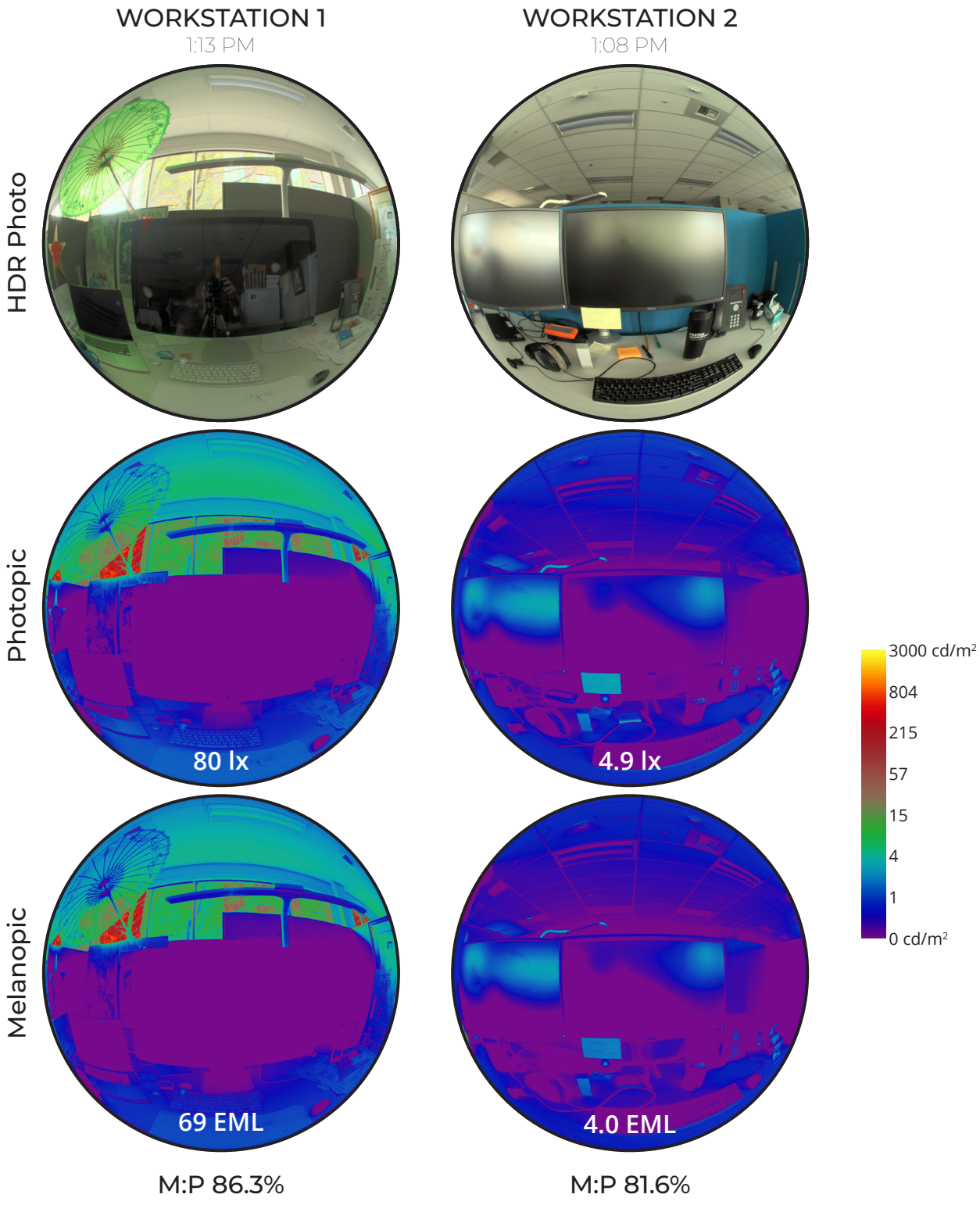




M:P 67.8%

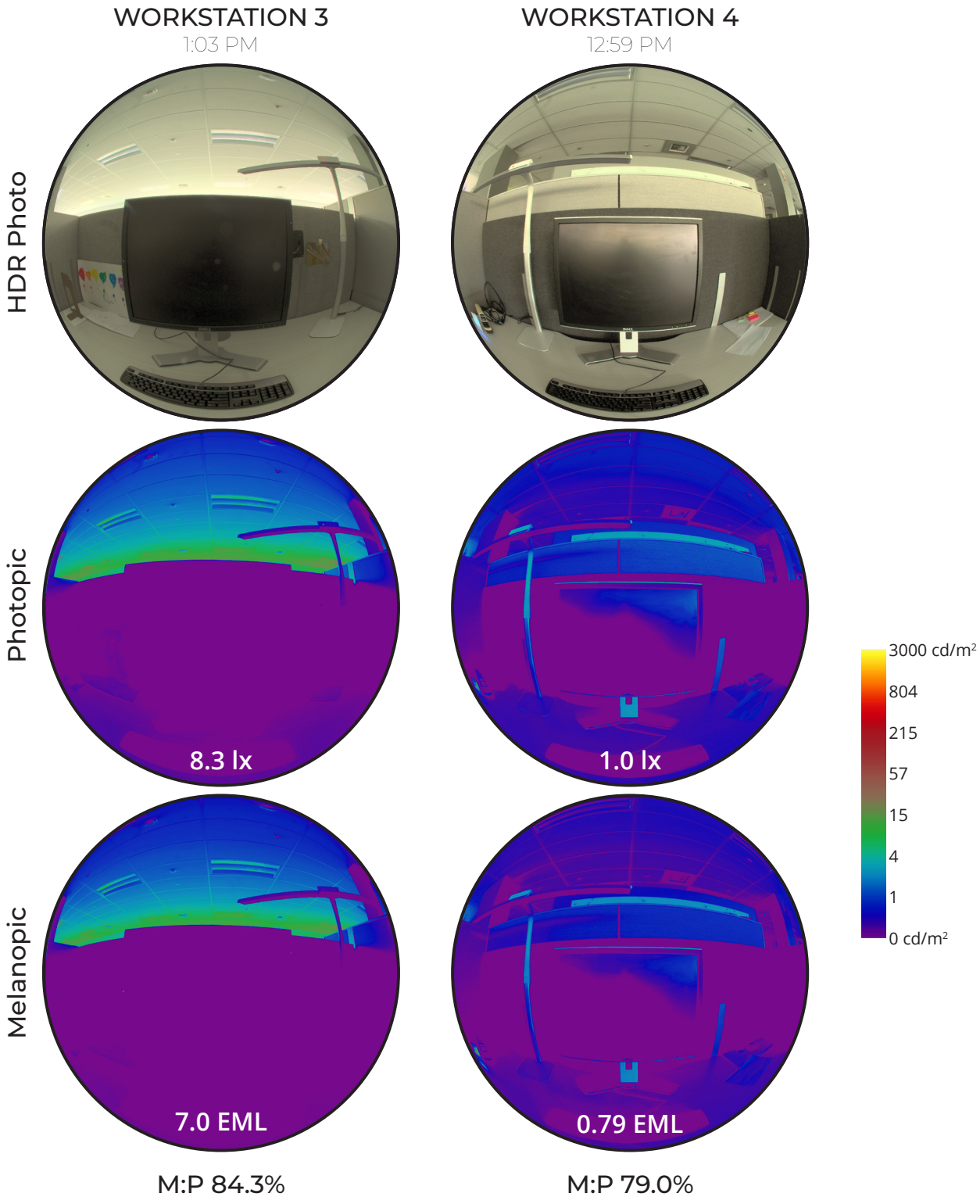
Study 3.1 - Level O-3 - Zone A - Daylight Only

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K



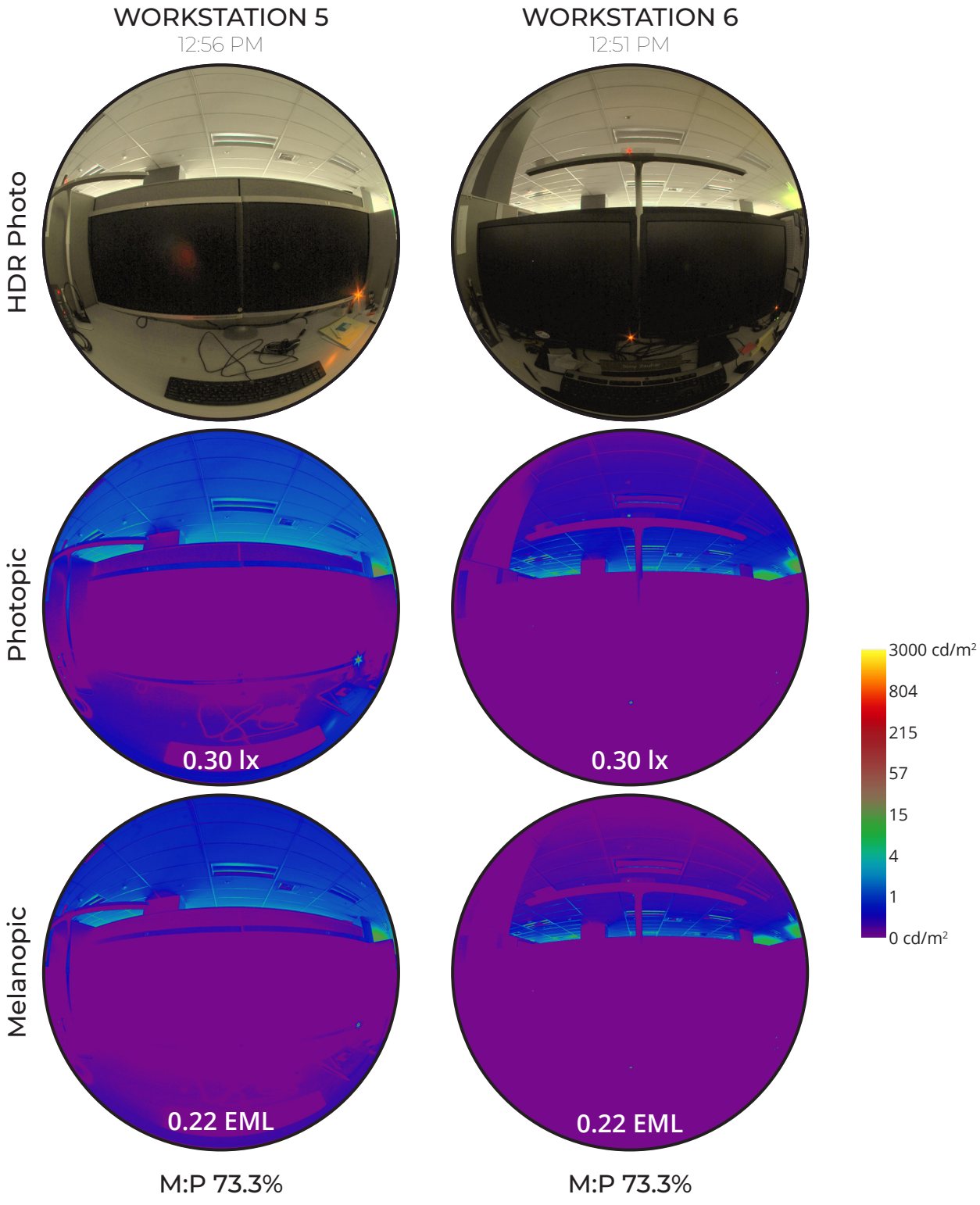
Study 3.1 - Level O-3 - Zone A - Daylight Only

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K



Study 3.1 - Level O-3 - Zone A - Daylight Only

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K



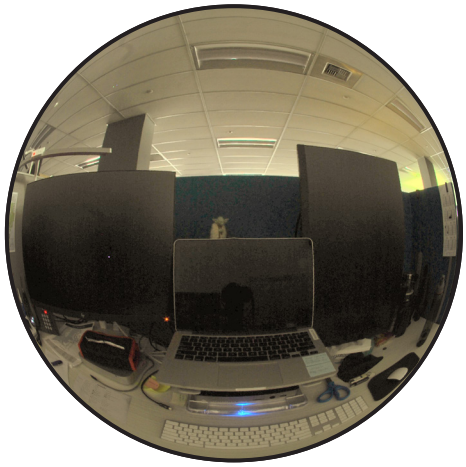
Study 3.1 - Level O-3 - Zone A - Daylight Only

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K

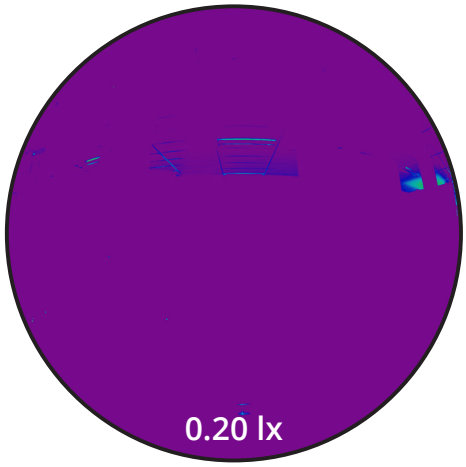
WORKSTATION 7

12:48 PM

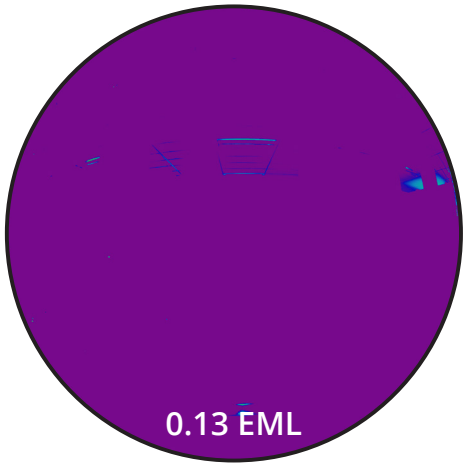
HDR Photo

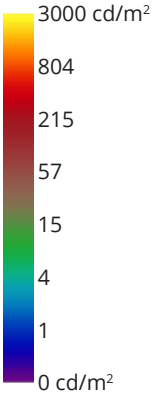


Photopic



Melanopic

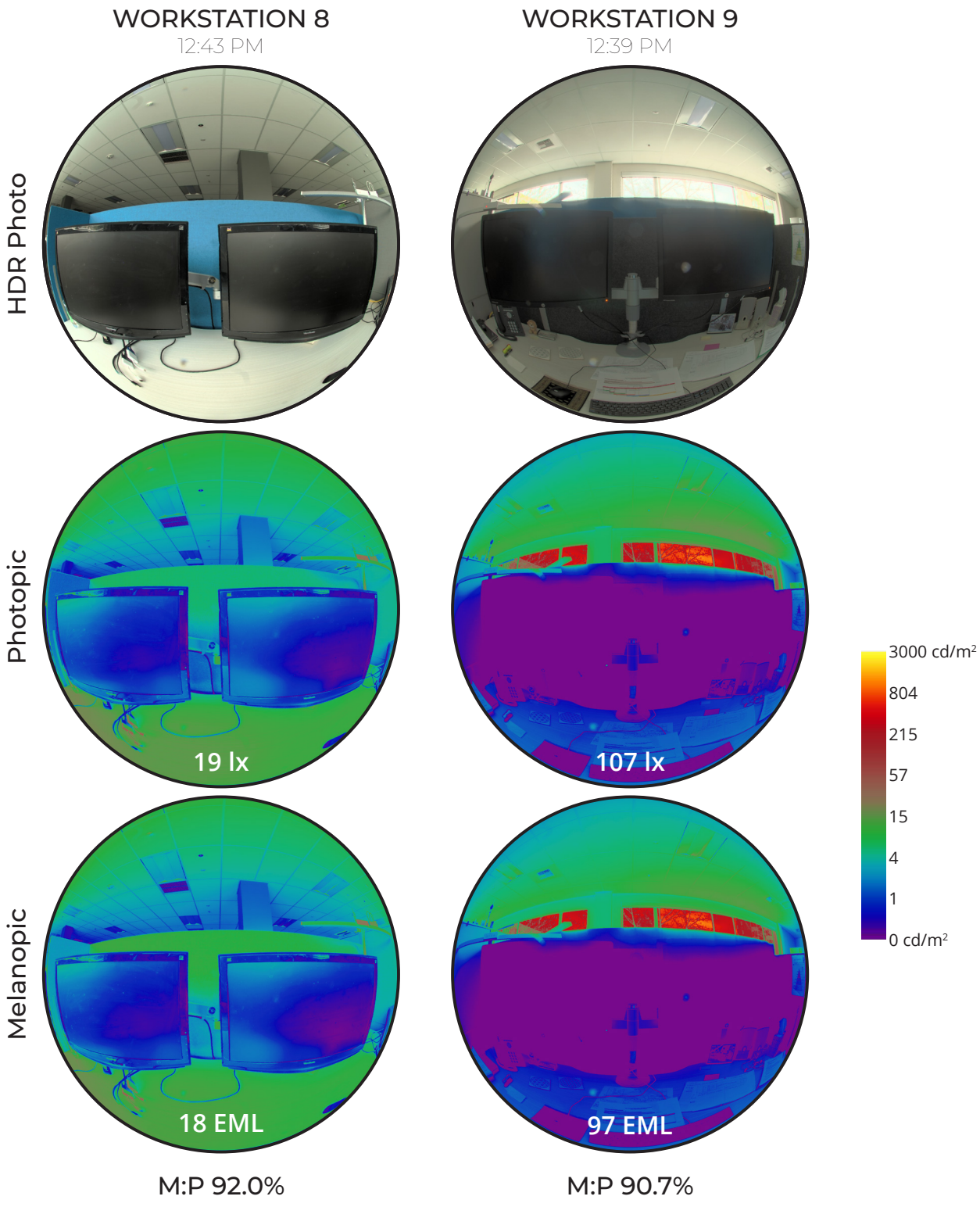




M:P 65.0%

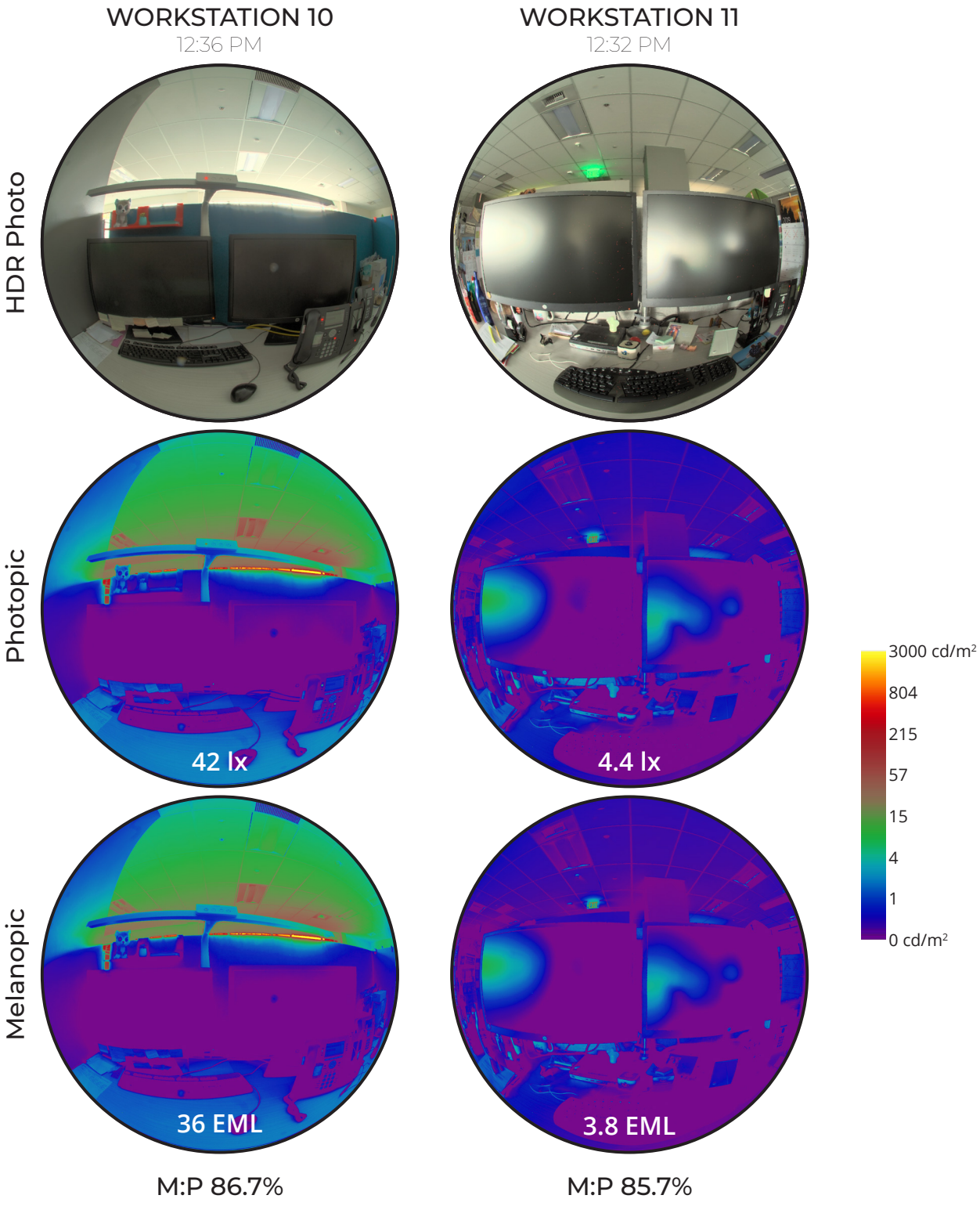
Study 3.1 - Level O-3 - Zone B - Daylight Only

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K



Study 3.1 - Level O-3 - Zone B - Daylight Only

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K



Study 3.1 - Level O-3 - Zone B - Daylight Only

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K

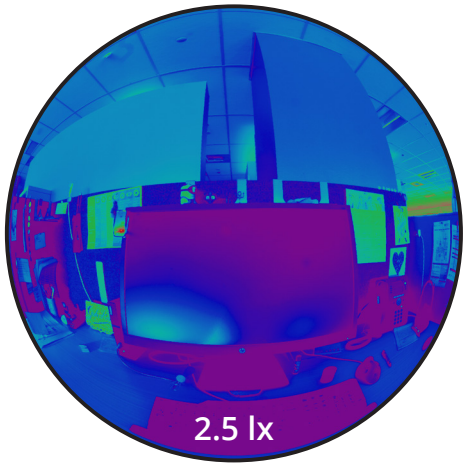
WORKSTATION 12

12:25 PM

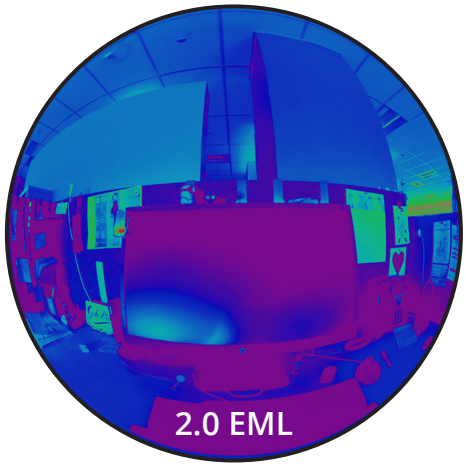
HDR Photo

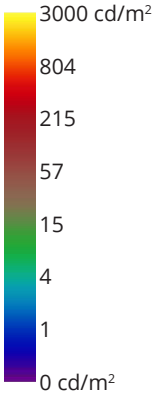


Photopic



Melanopic

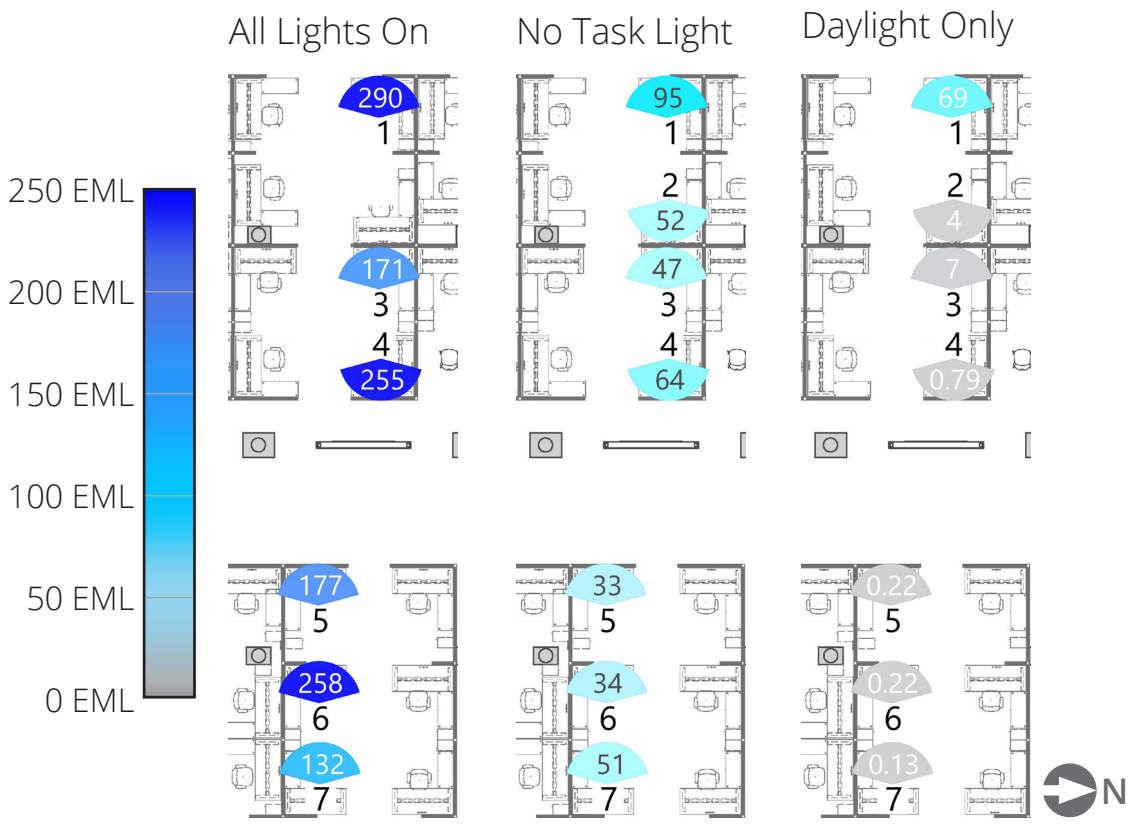


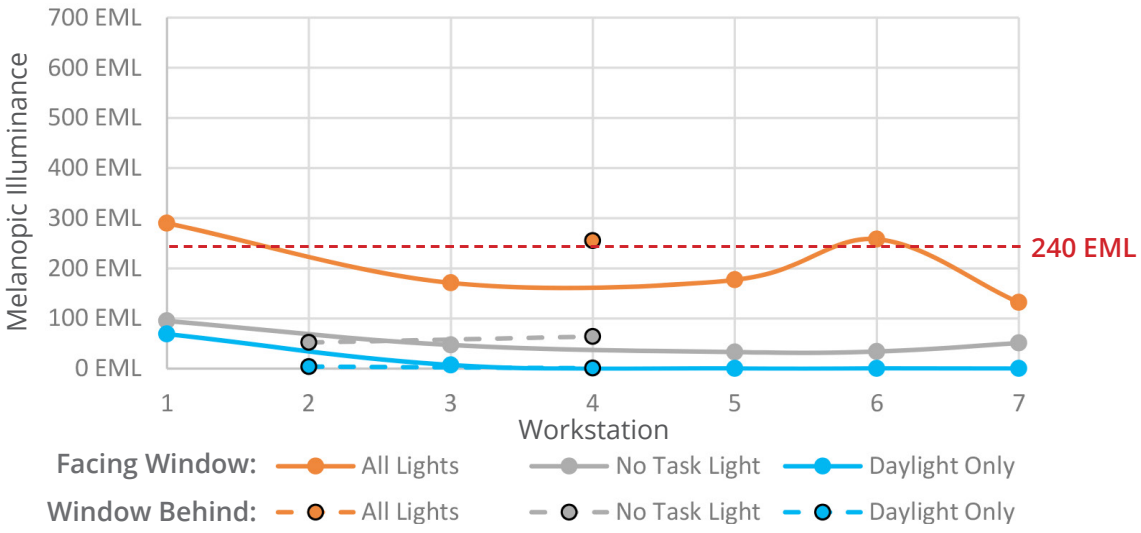


M:P 81.6%

Study 3.1 - Level O-3 - Zone A - Melanopic Illuminance

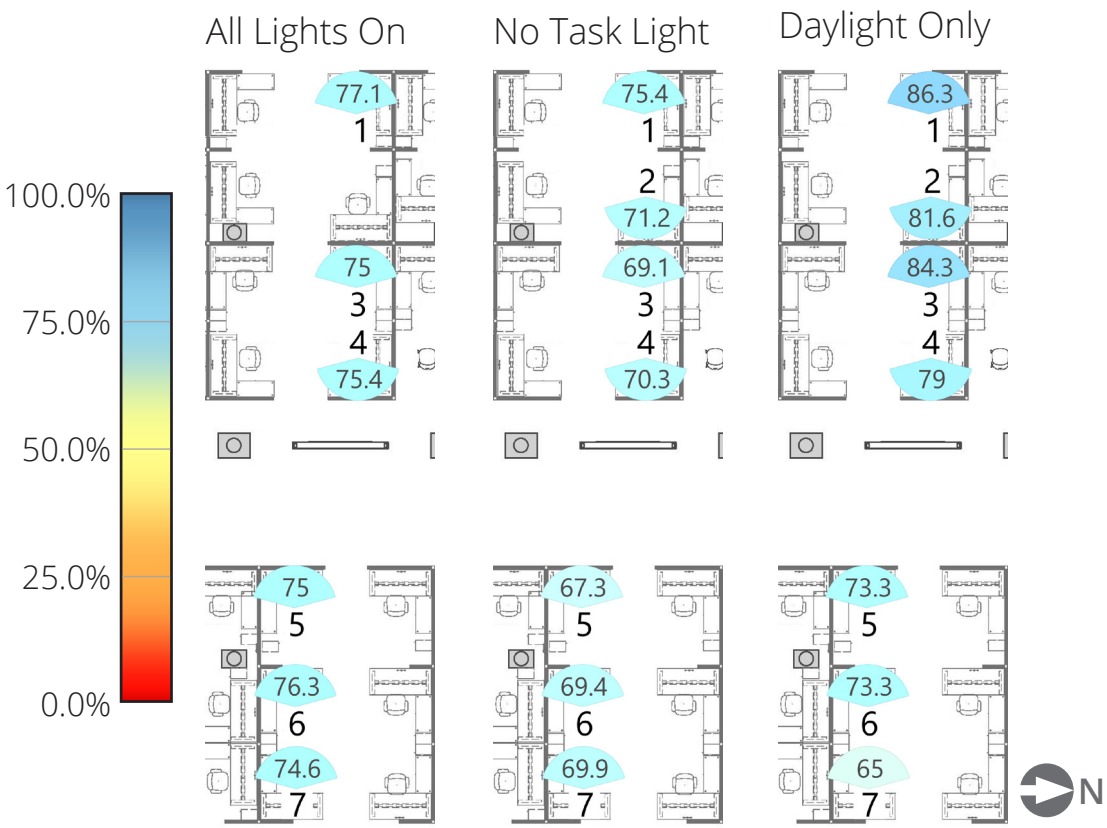
Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K

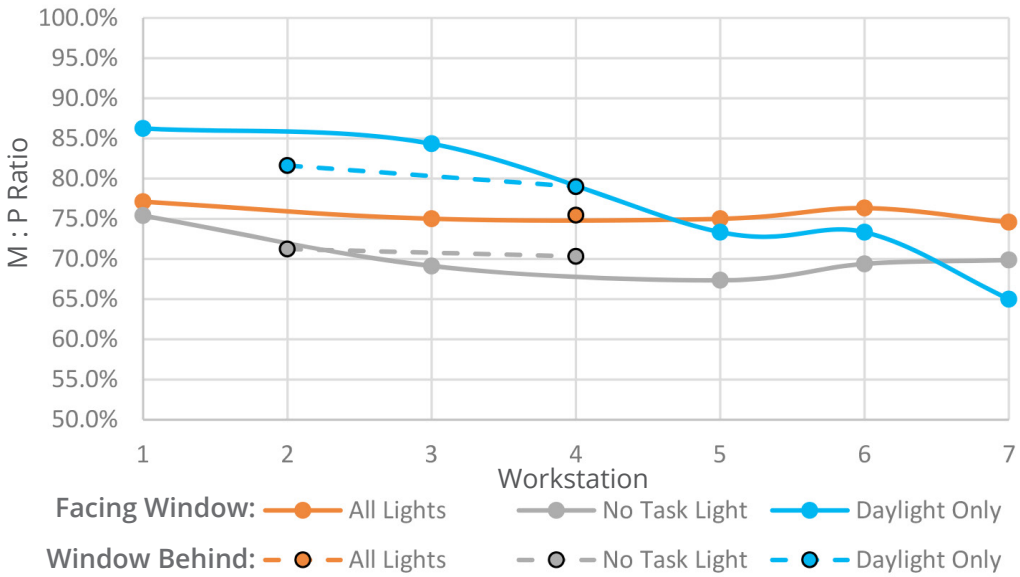




Study 3.1 - Level O-3 - Zone A - Melanopic : Photopic Ratio

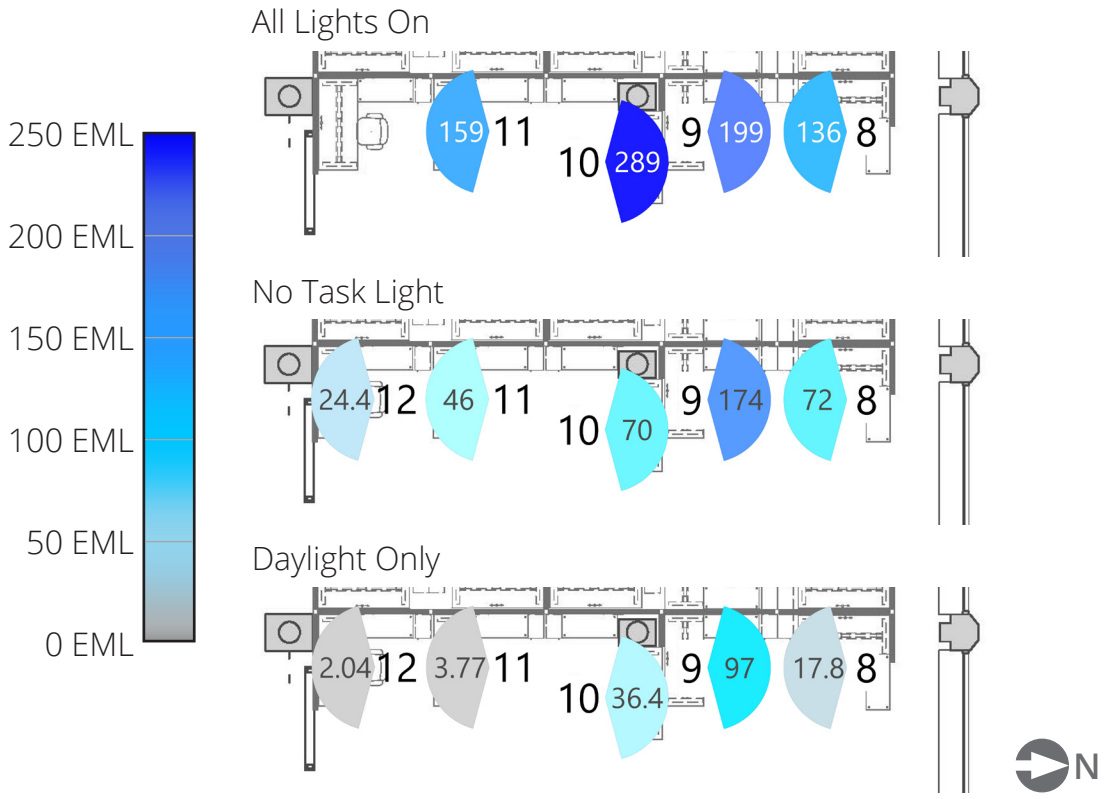
Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K

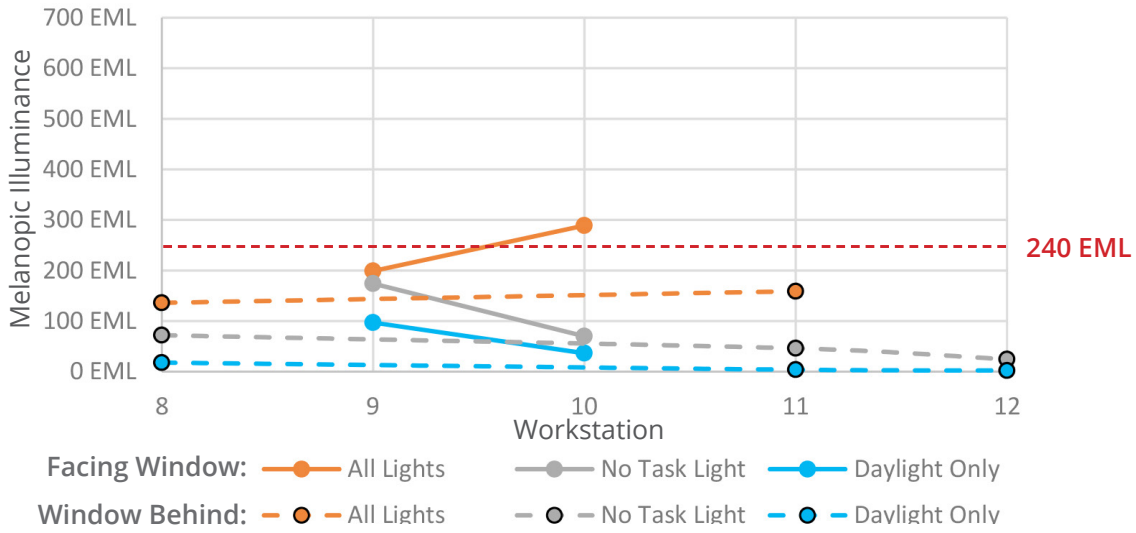




Study 3.1 - Level O-3 - Zone B - Melanopic Illuminance

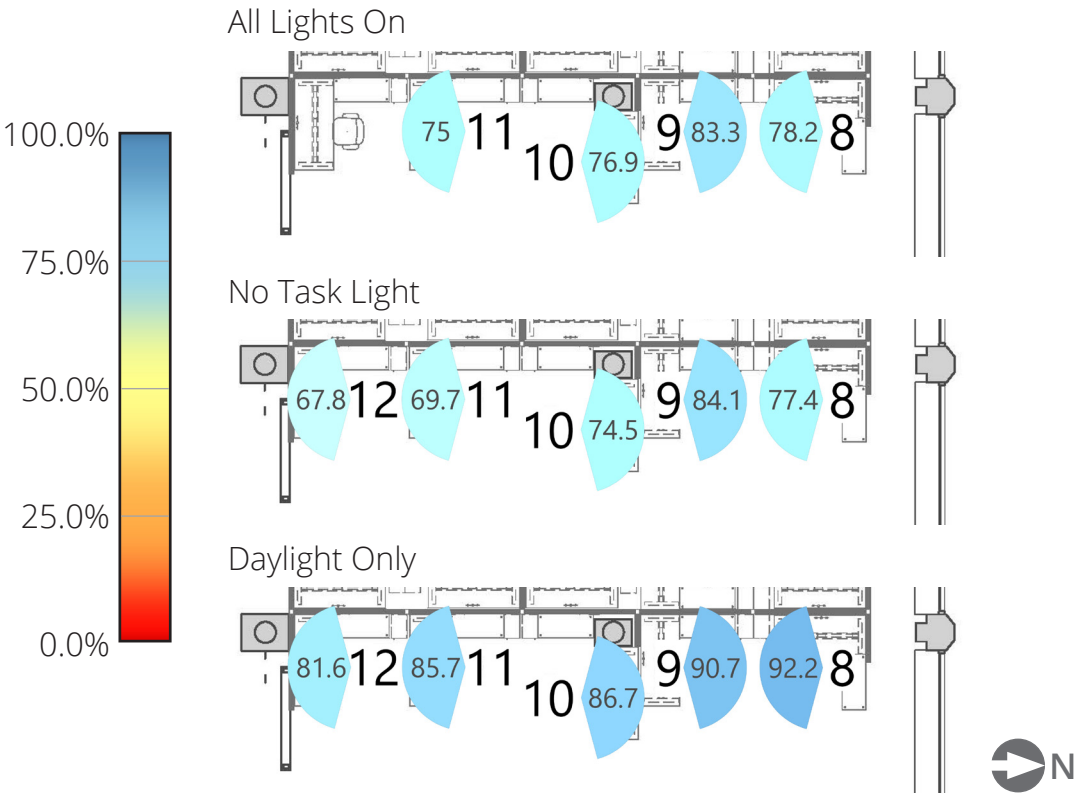
Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K

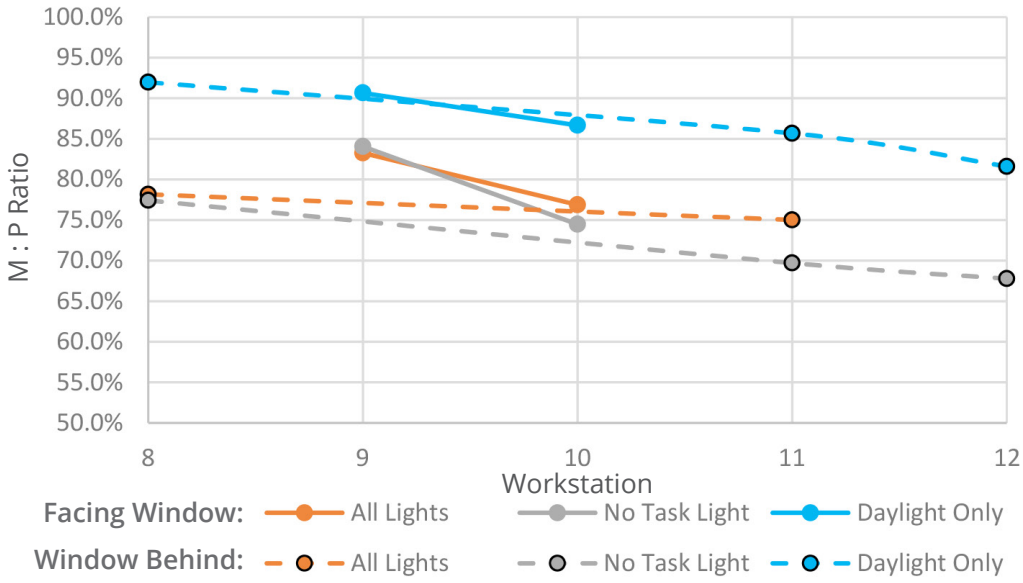




Study 3.1 - Level O-3 - Zone B - Melanopic : Photopic Ratio

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 87 w/m²
Ambient Lighting Color Temp: 4000K

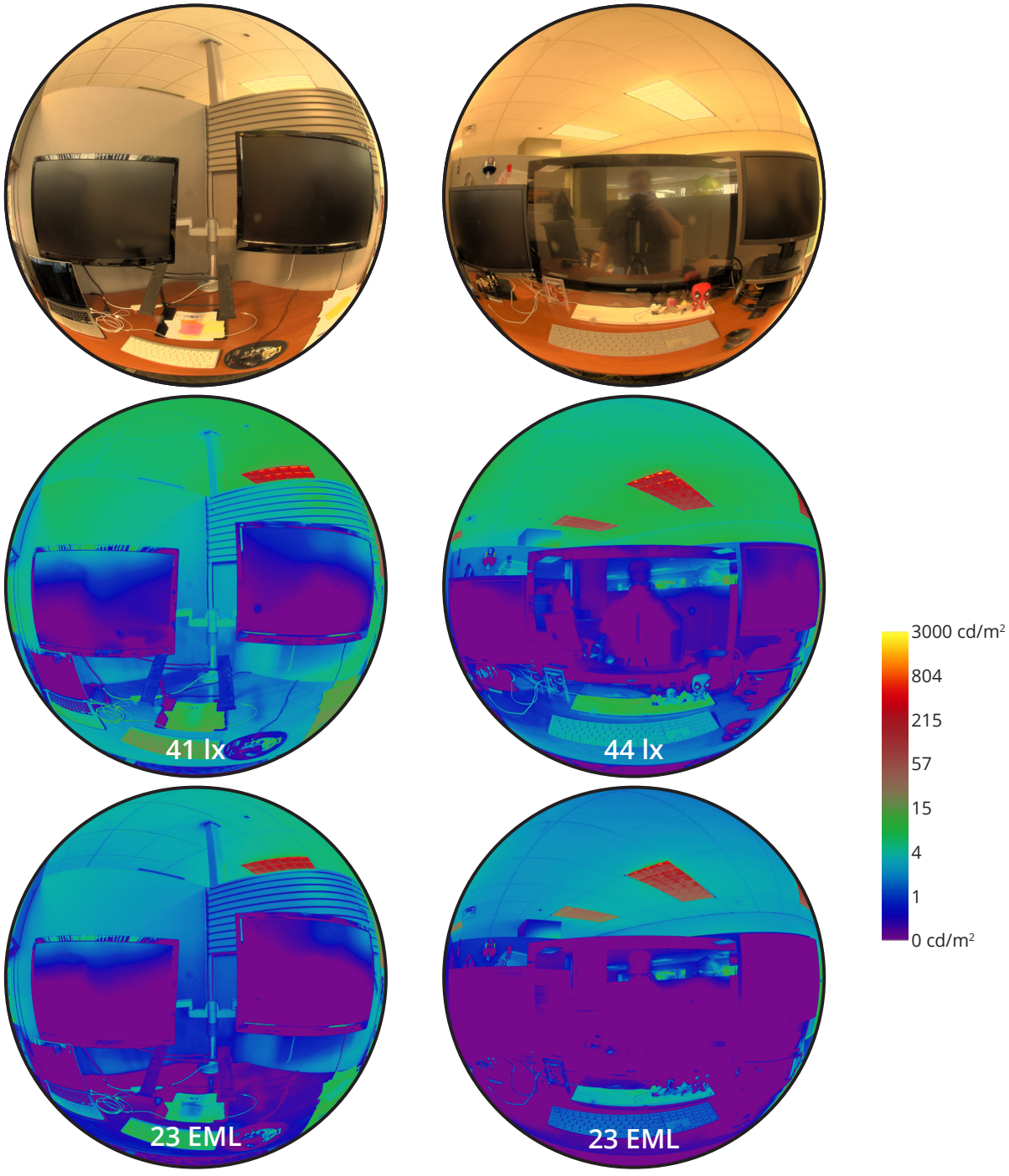




Study 3.2 - Level C-1 - Zone C - All Lights On

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 289 w/m²
Ambient Lighting Color Temp: 3500K

WORKSTATION 1	WORKSTATION 2
1:39 PM	1:43 PM



M:P 56.1%	M:P 52.3%

Study 3.2 - Level C-1 - Zone C - All Lights On

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 289 w/m²
Ambient Lighting Color Temp: 3500K

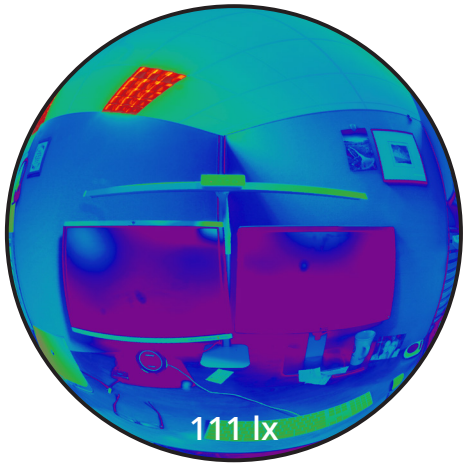
WORKSTATION 3

1:47 PM

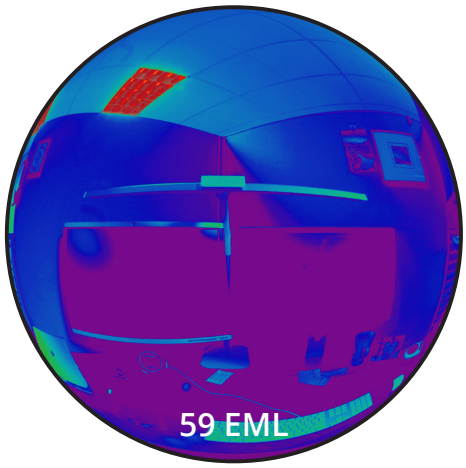
HDR Photo

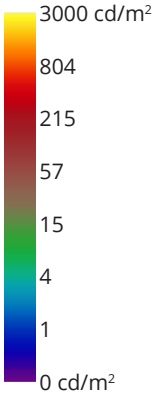


Photopic



Melanopic

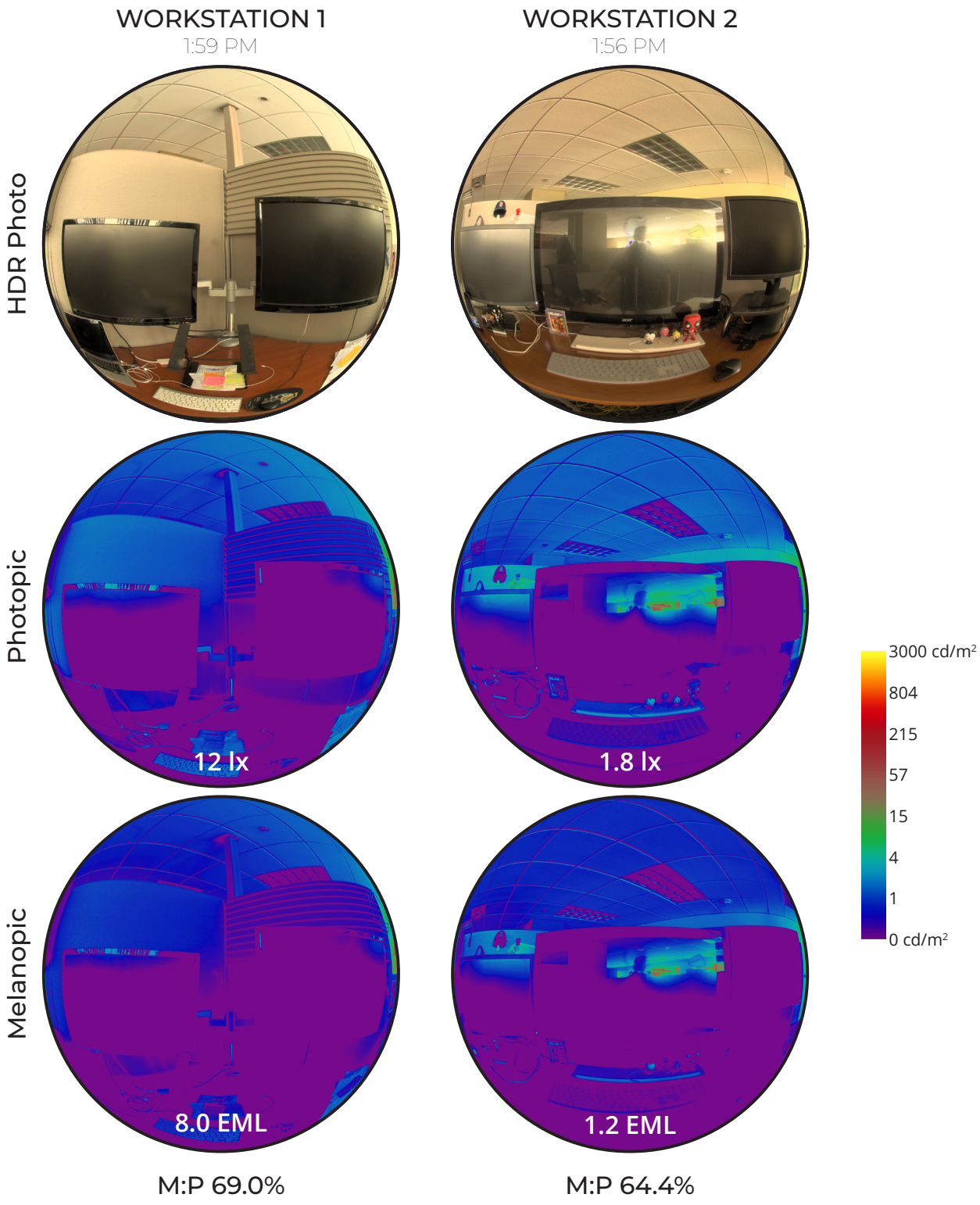




M:P 56.1%

Study 3.2 - Level C-1 - Zone C - Daylight Only

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 289 w/m²
Ambient Lighting Color Temp: 3500K



Study 3.2 - Level C-1 - Zone C - Daylight Only

Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 289 w/m²
Ambient Lighting Color Temp: 3500K

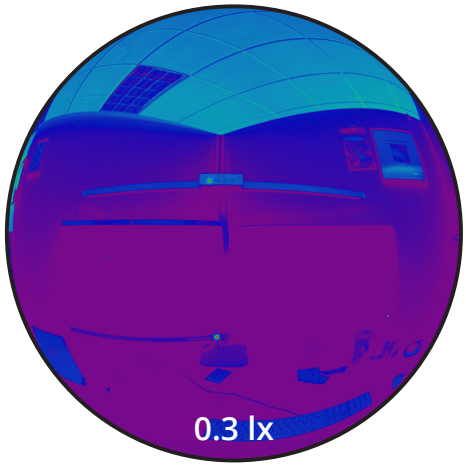
WORKSTATION 3

1:52 PM

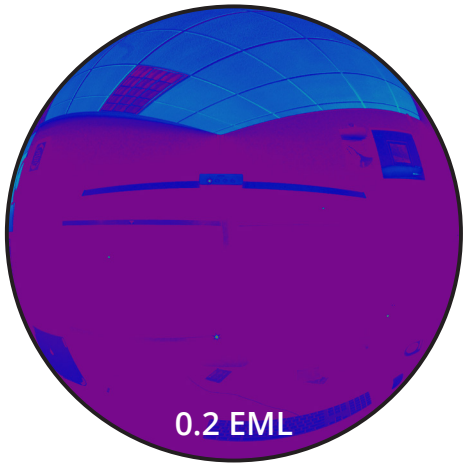
HDR Photo

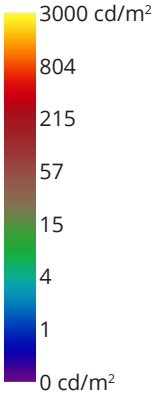


Photopic



Melanopic

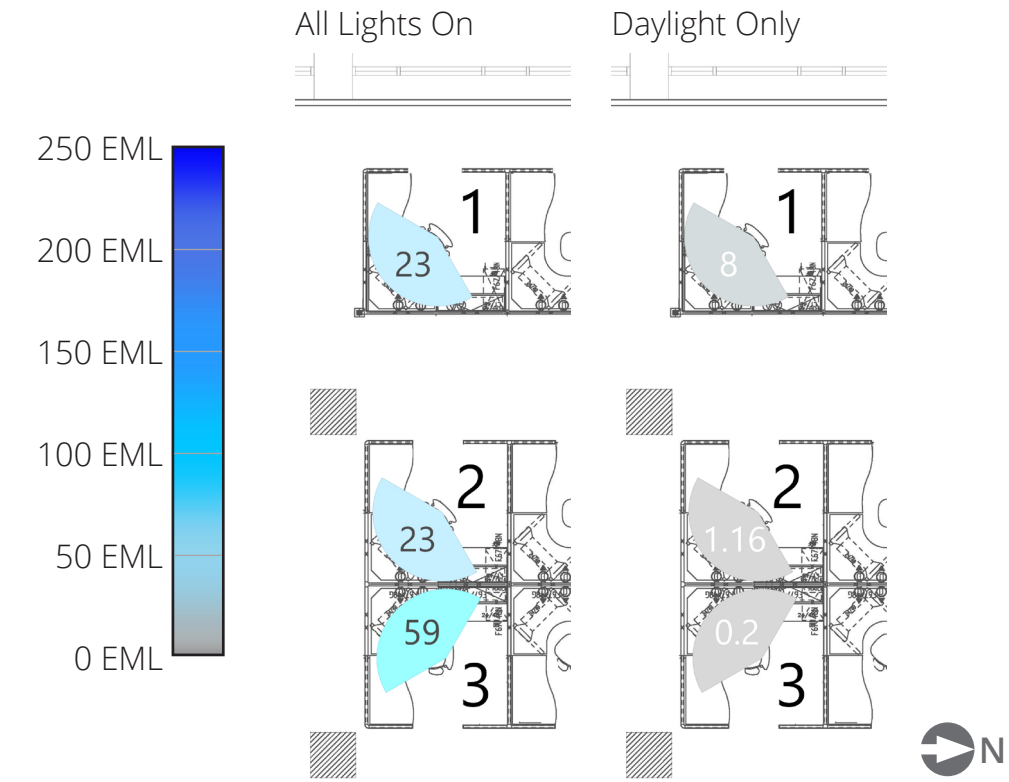


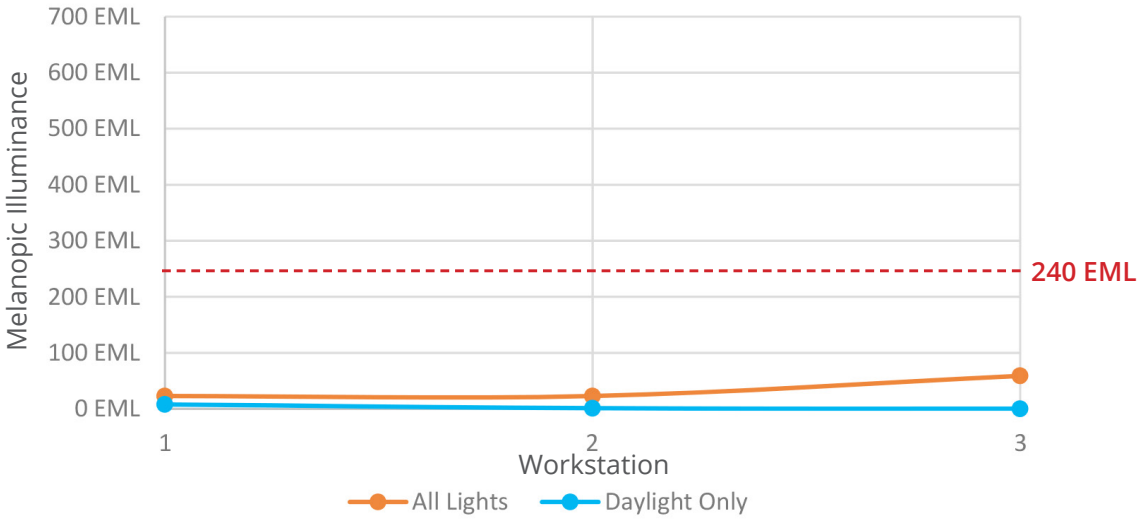


M:P 66.7%

Study 3.2 - Level C-1 - Zone C - Melanopic Illuminance

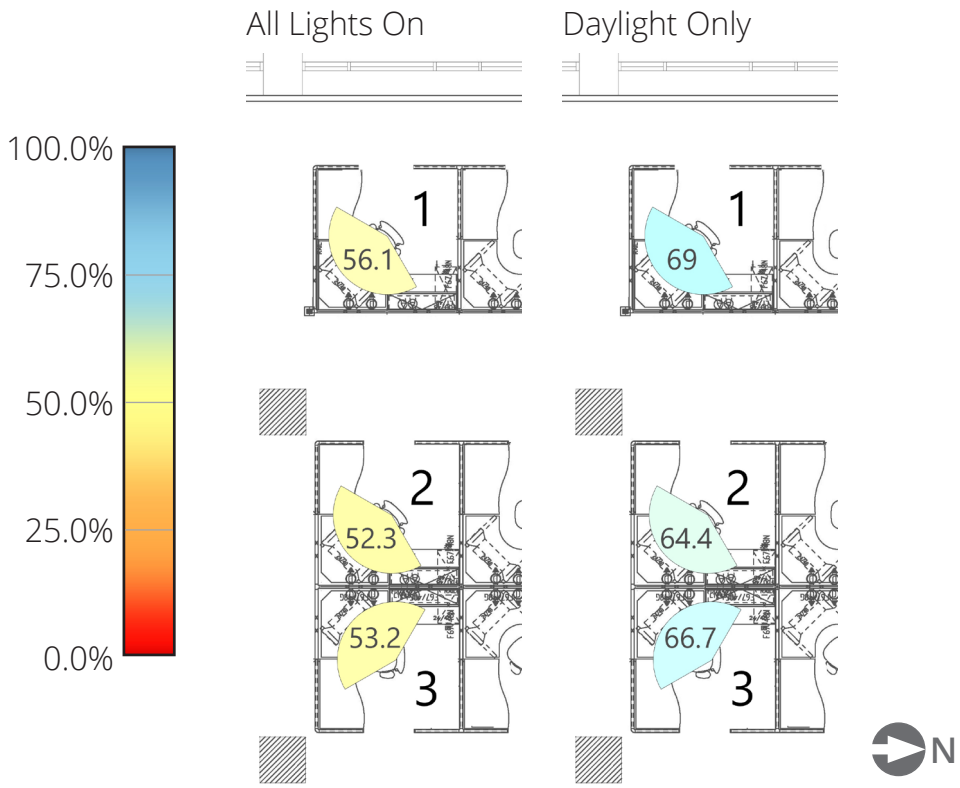
Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 289 w/m²
Ambient Lighting Color Temp: 3500K

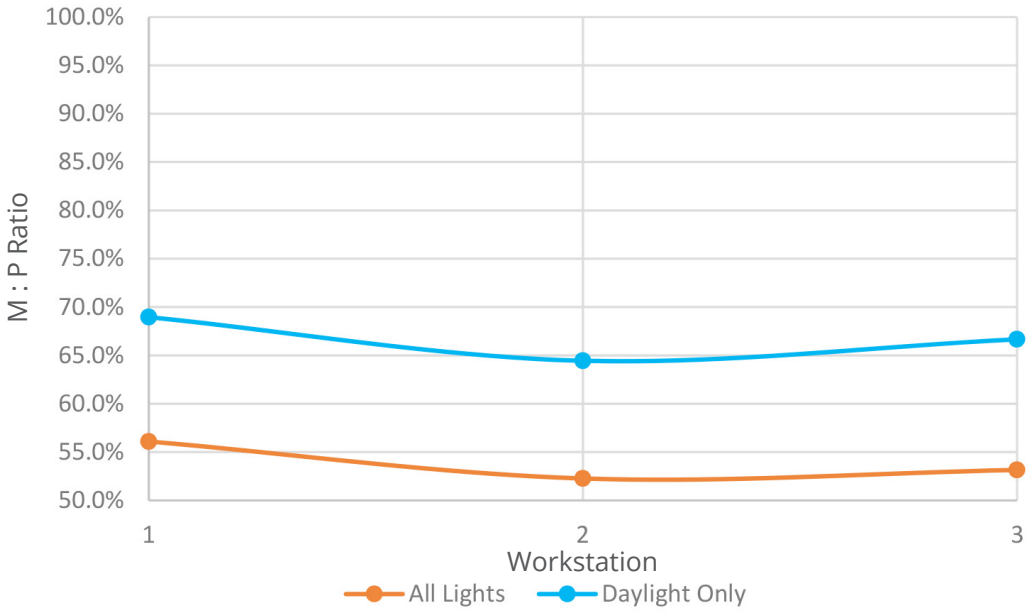




Study 3.2 - Level C-1 - Zone C - Melanopic : Photopic Ratio

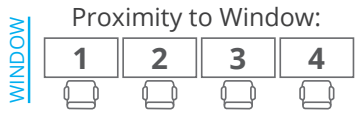
Date: Saturday, April 13th
Weather: Overcast
Global Horizontal Solar Irradiance: 289 w/m²
Ambient Lighting Color Temp: 3500K



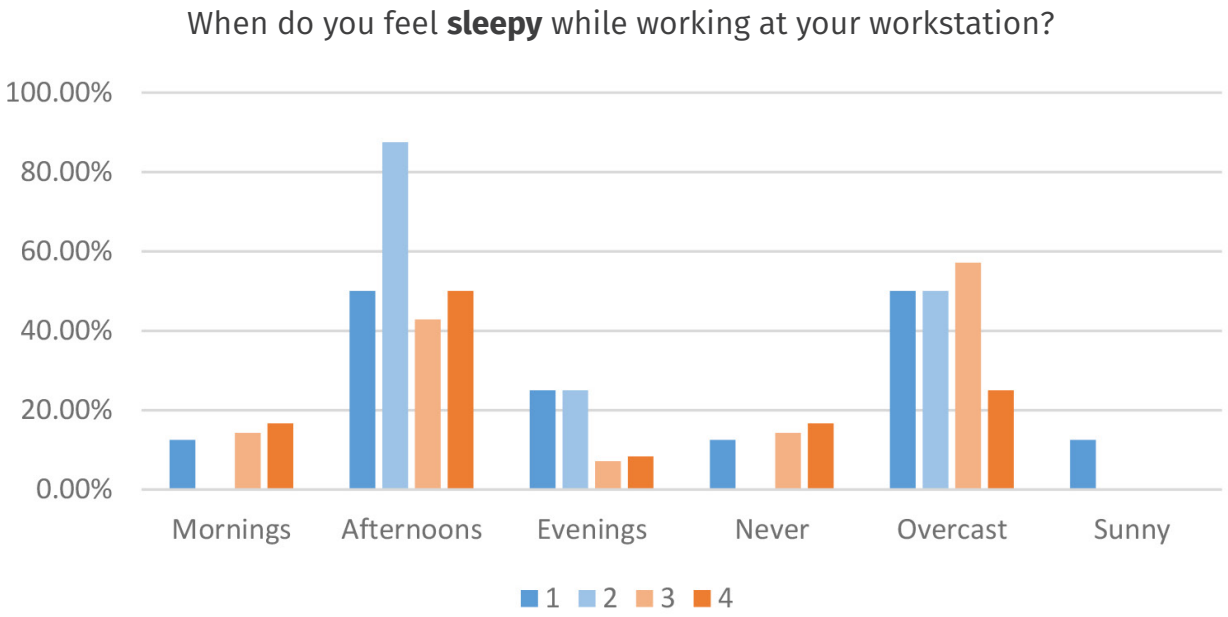


Appendix B: Workplace Lighting Survey Results

Case Study 1 - Ankrom Moisan Office - 41 Responses



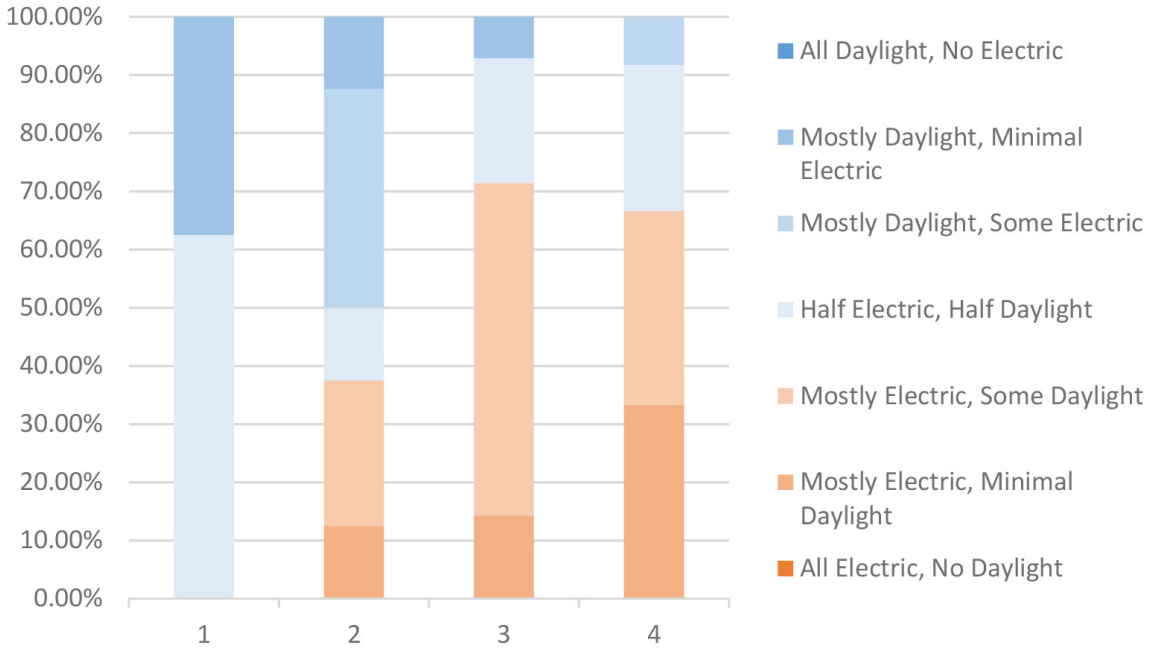




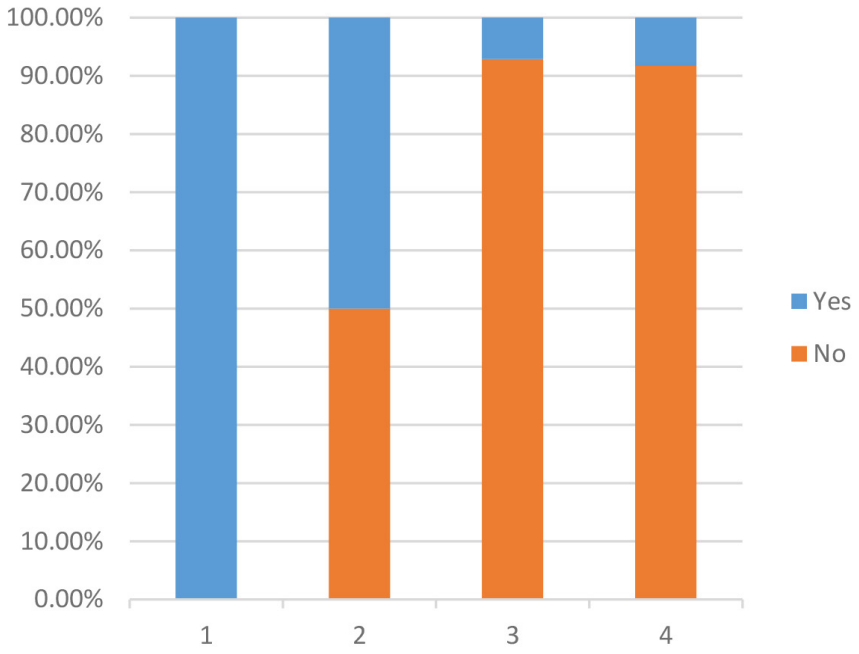
Case Study 1 - Ankrom Moisan Office - 41 Responses



Is your workstation primarily lit by **daylight or electric light**?



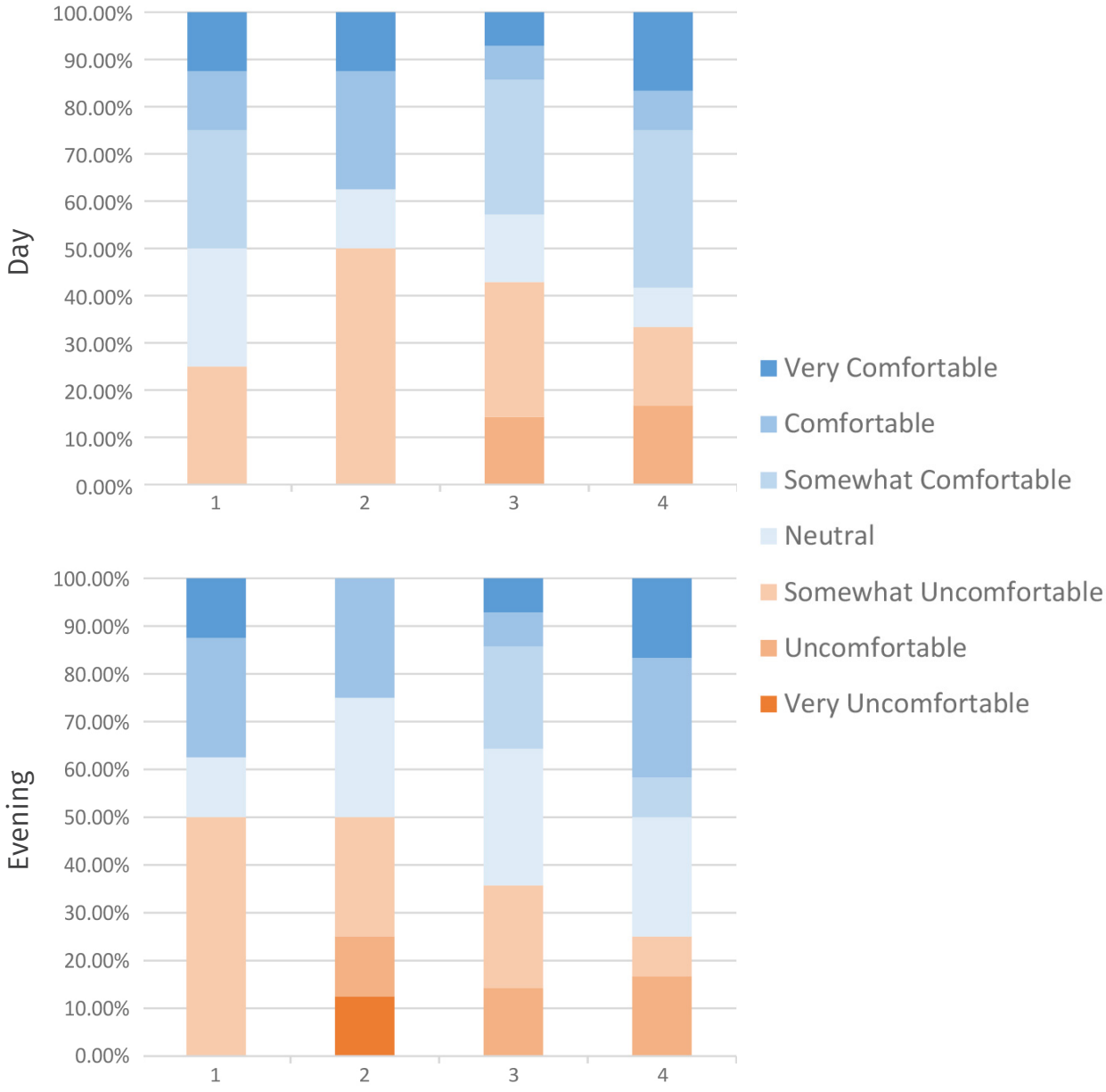
Can you see the **sky** while sitting at your workstation?



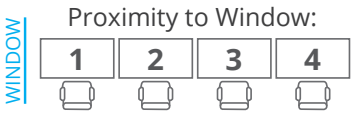
Case Study 1 - Ankrom Moisan Office - 41 Responses



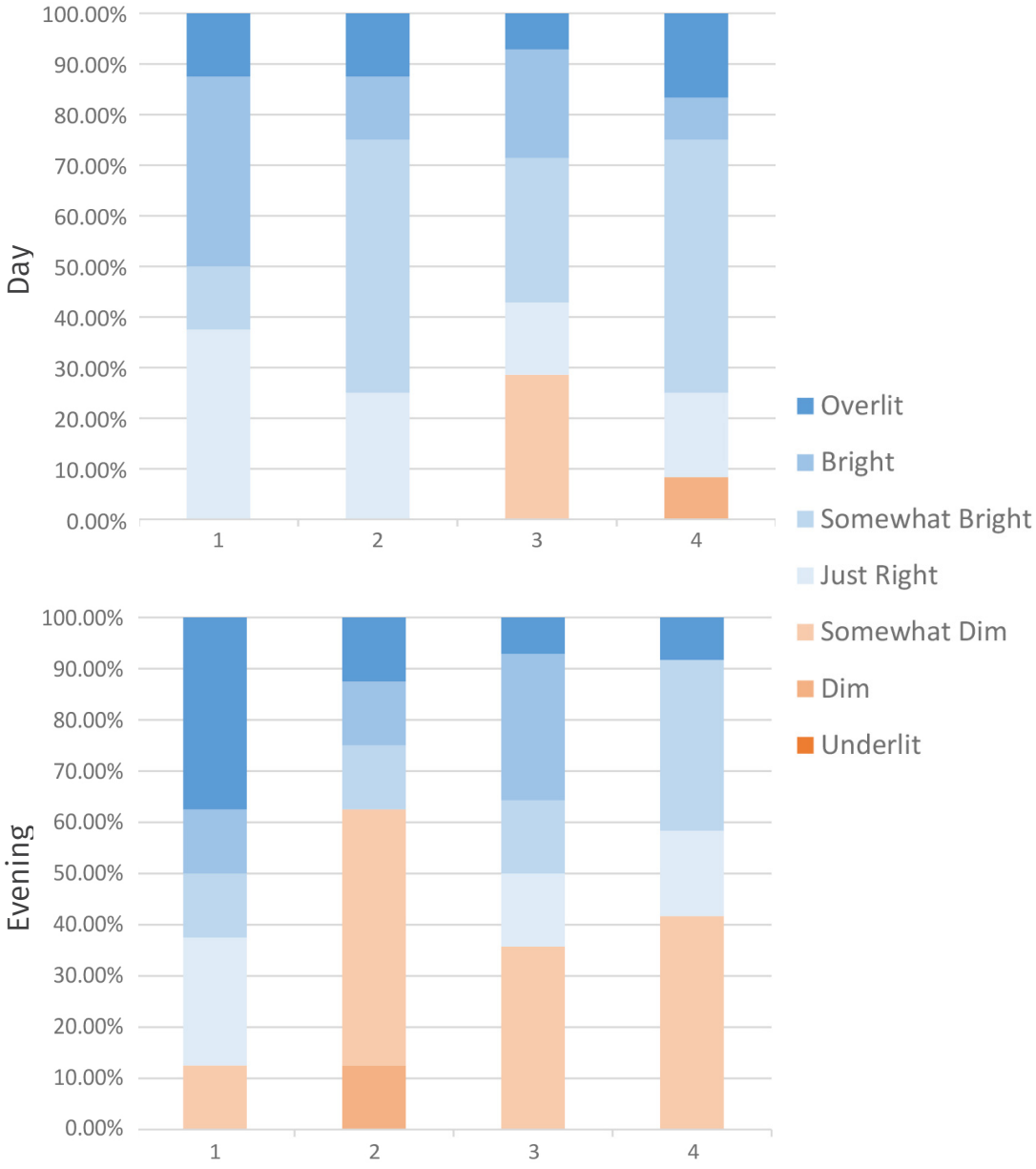
How **comfortable** is the light at your workstation?



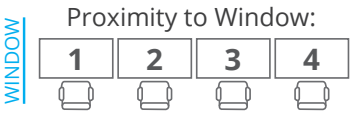
Case Study 1 - Ankrom Moisan Office - 41 Responses



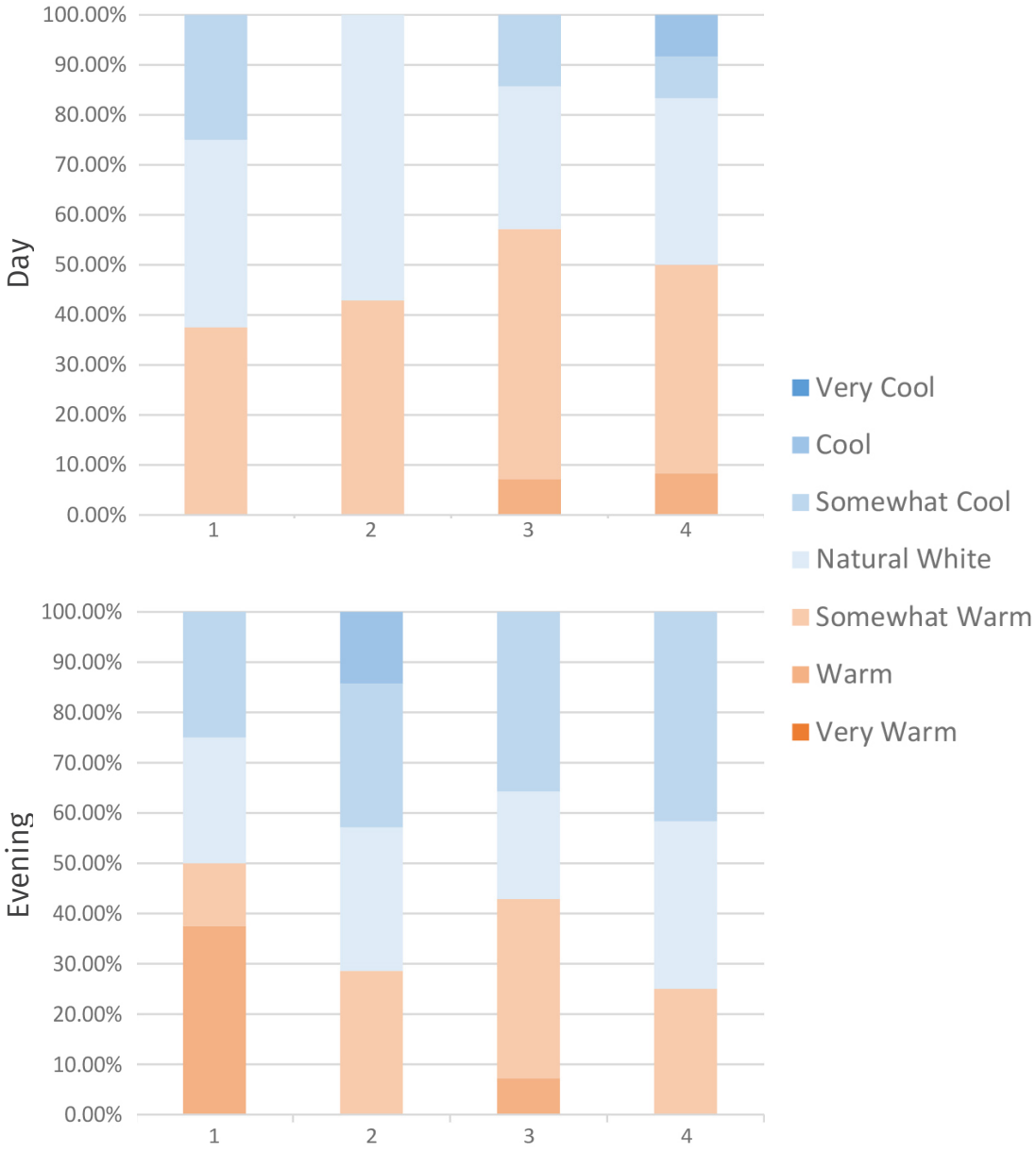
How **bright** is the light at your workstation?



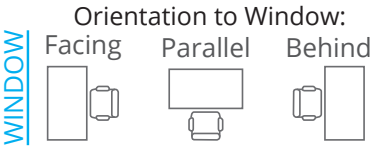
Case Study 1 - Ankrom Moisan Office - 41 Responses

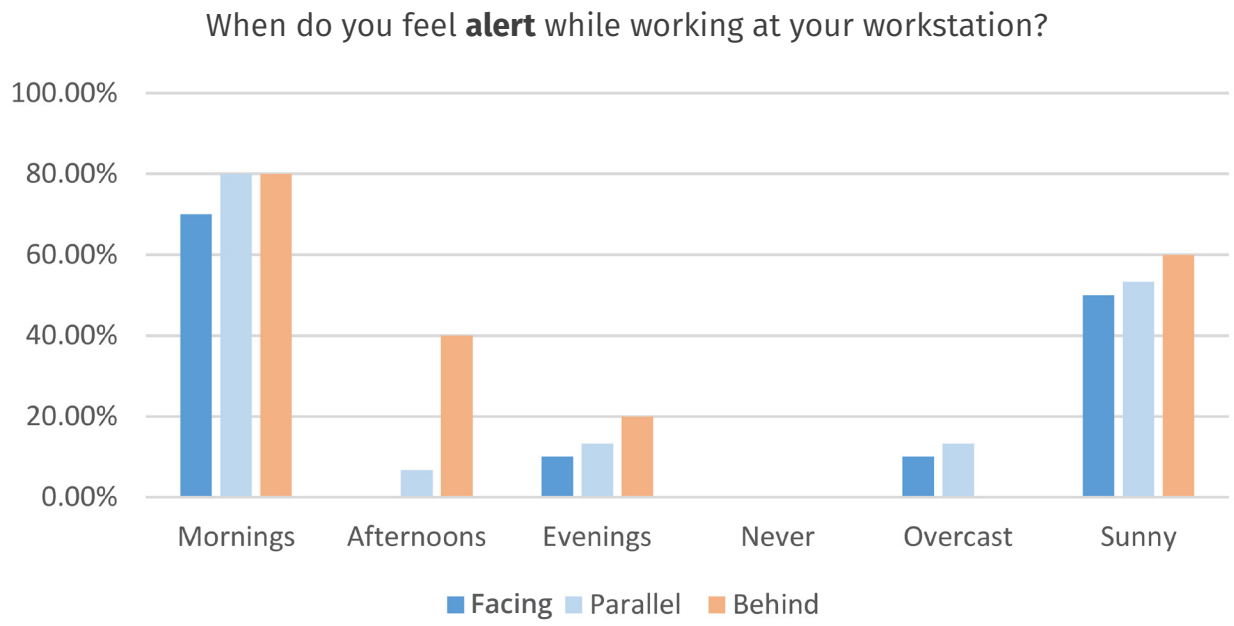


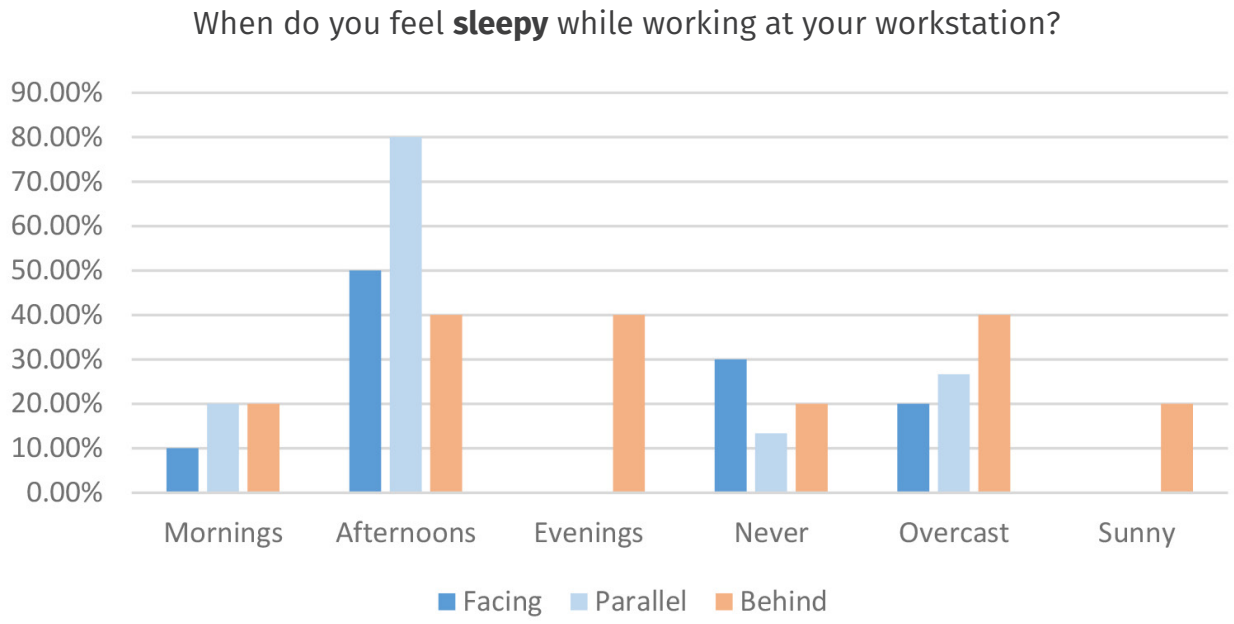
What **color** is the light at your workstation?



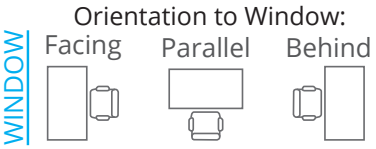
Case Study 2 - Weber Thompson Office - 33 Responses



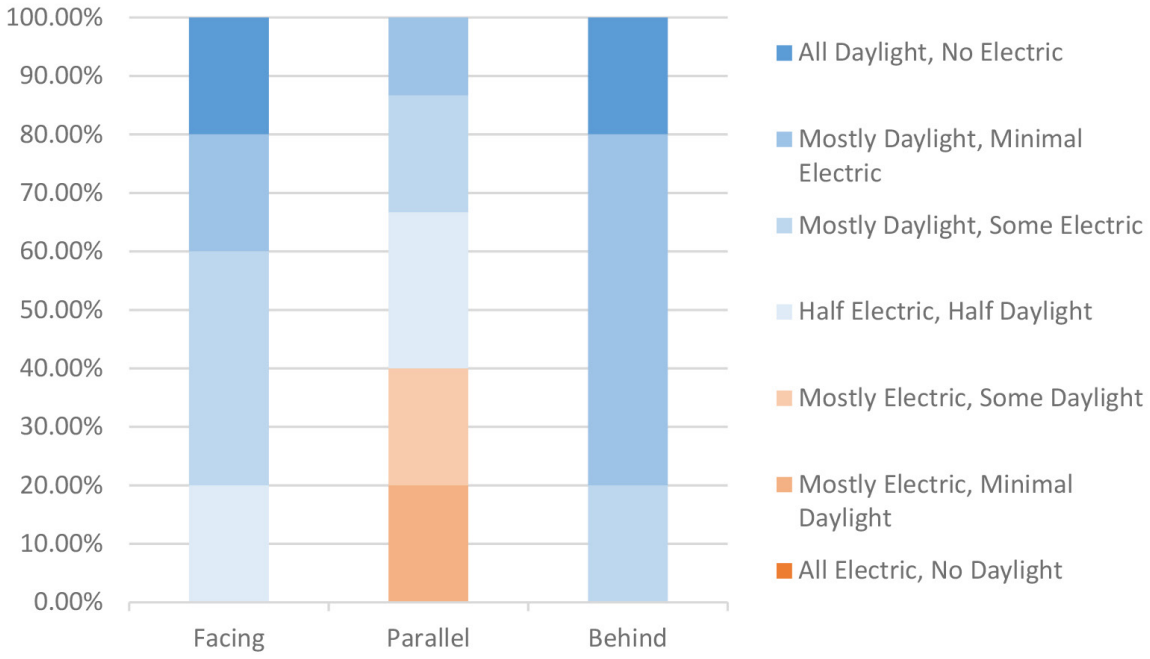




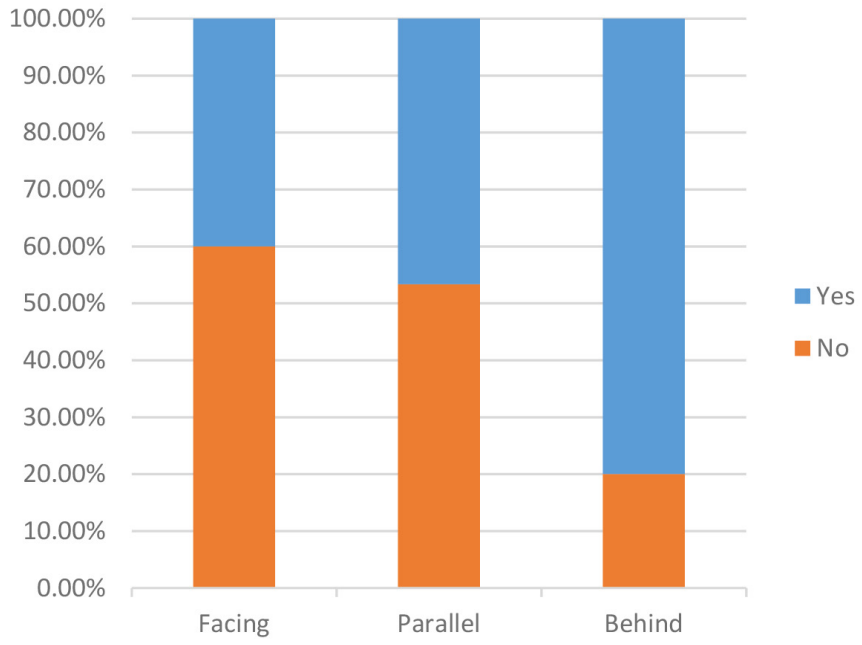
Case Study 2 - Weber Thompson Office - 33 Responses



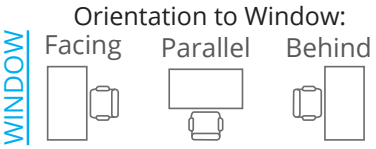
Is your workstation primarily lit by **daylight or electric light**?



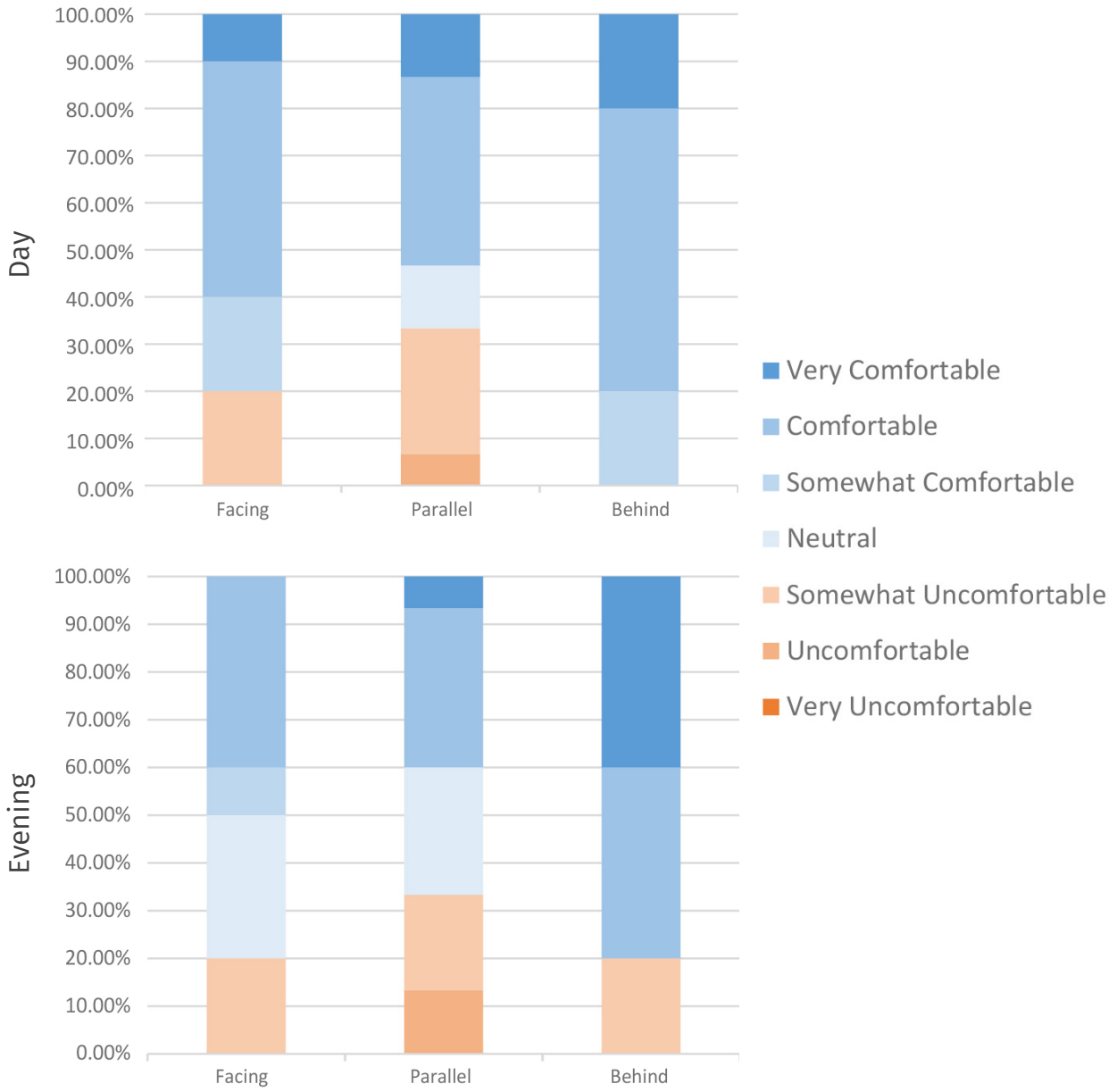
Can you see the **sky** while sitting at your workstation?



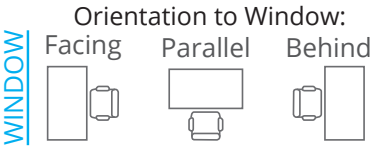
Case Study 2 - Weber Thompson Office - 33 Responses

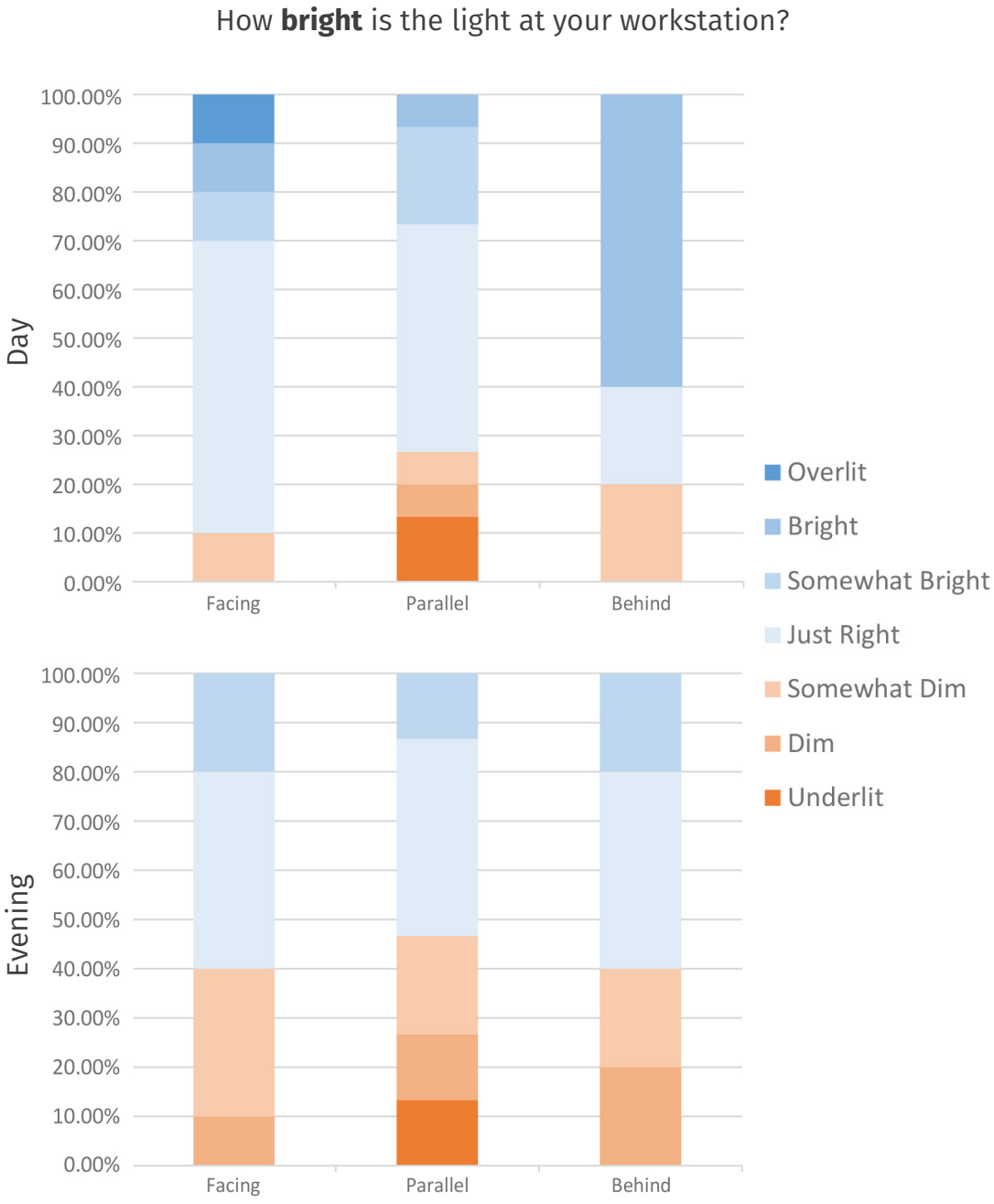


How **comfortable** is the light at your workstation?

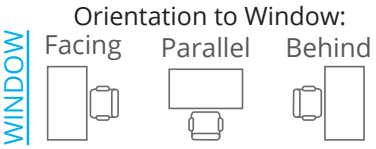


Case Study 2 - Weber Thompson Office - 33 Responses

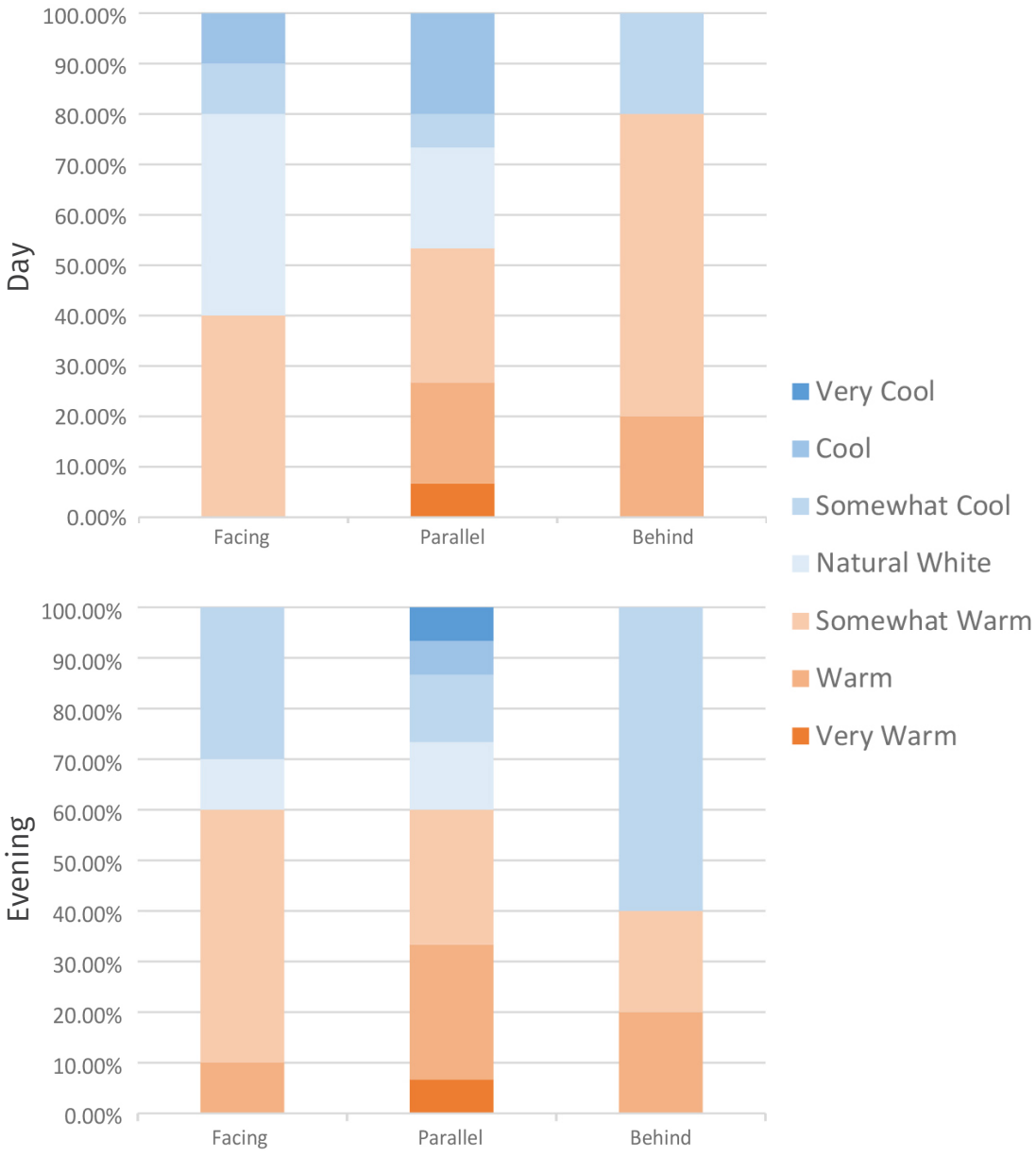




Case Study 2 - Weber Thompson Office - 33 Responses



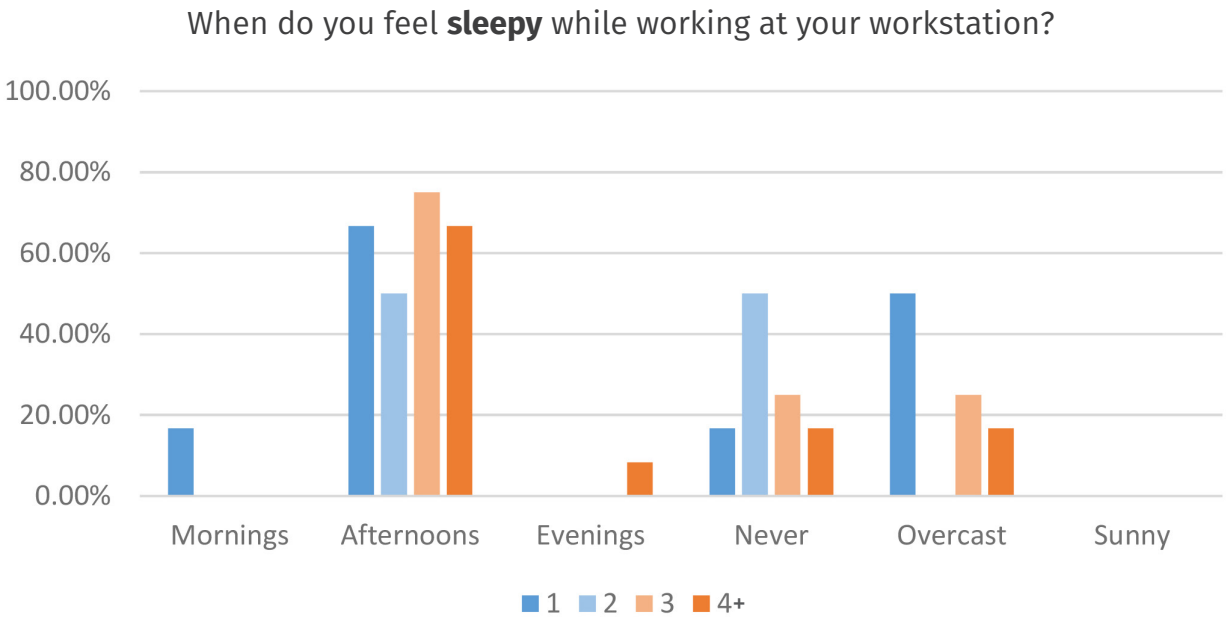
What **color** is the light at your workstation?



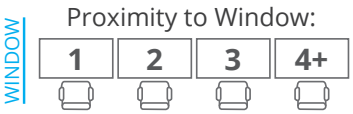
Case Study 3 - UW Tower (levels O-3 and C-3) - 21 Responses



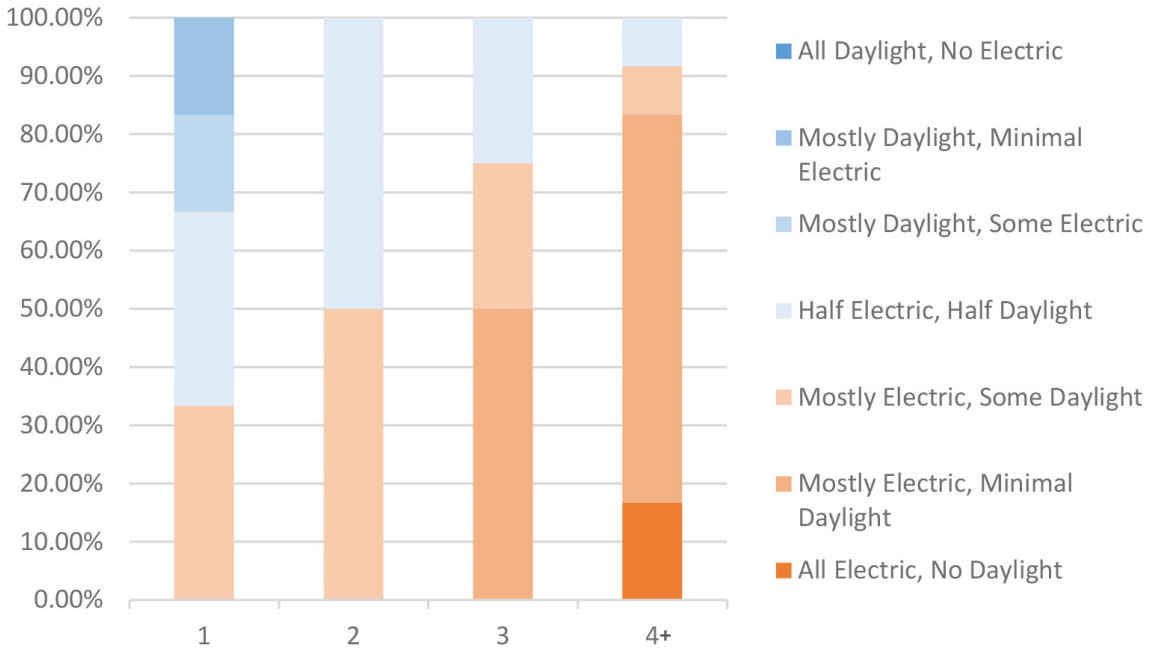




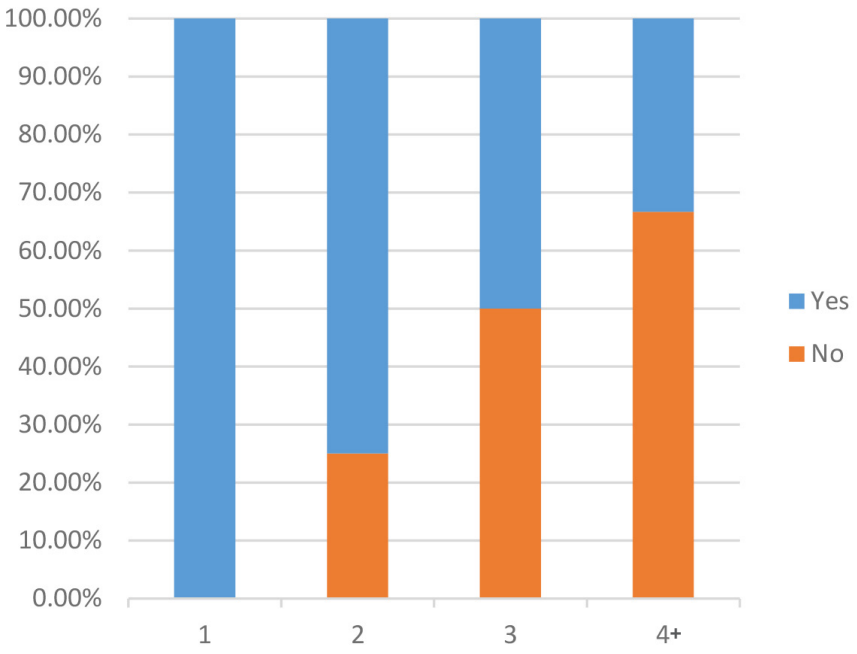
Case Study 3 - UW Tower (levels O-3 and C-3) - 21 Responses



Is your workstation primarily lit by **daylight or electric light**?



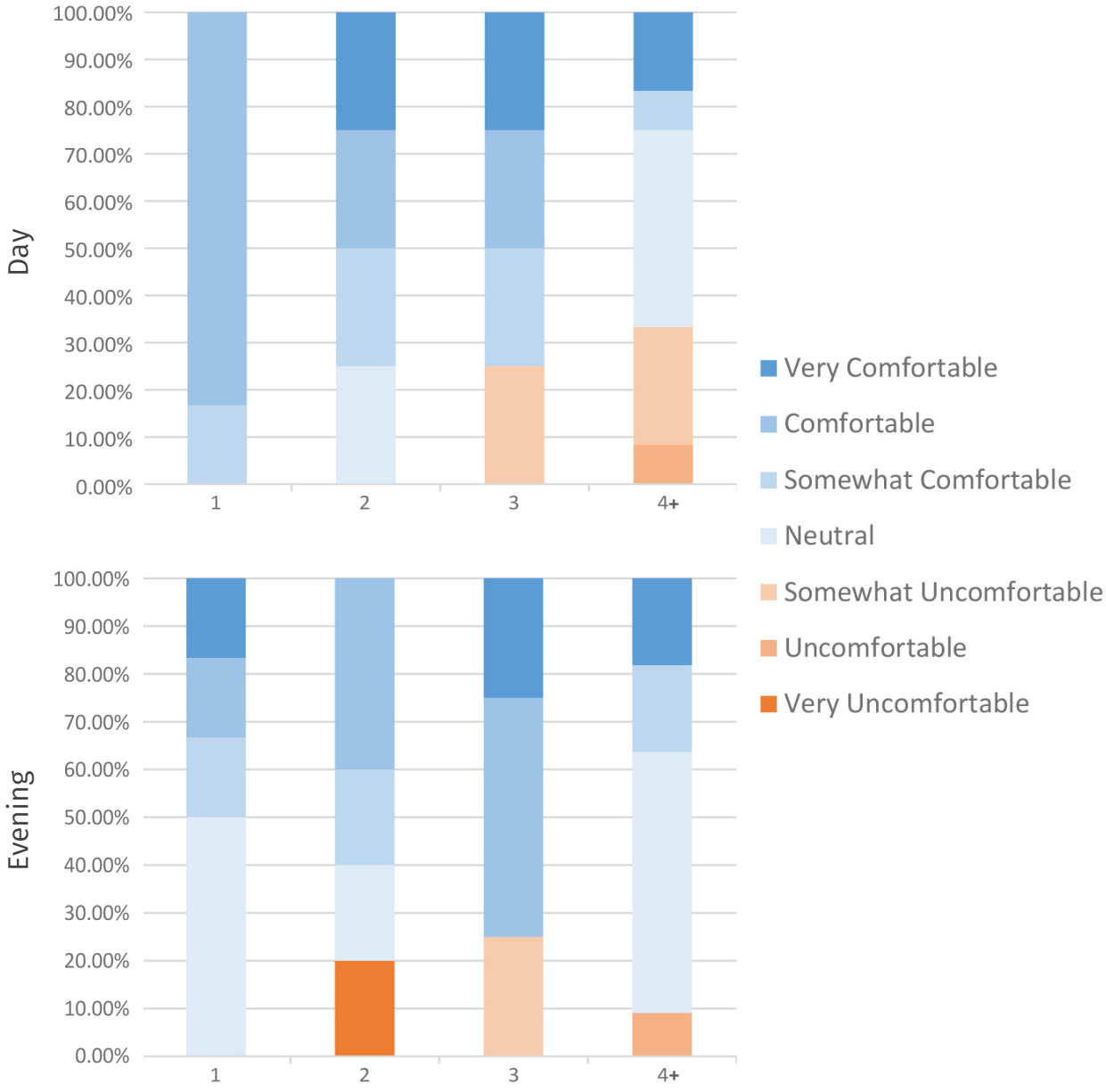
Can you see the **sky** while sitting at your workstation?



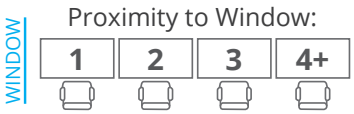
Case Study 3 - UW Tower (levels O-3 and C-3) - 21 Responses

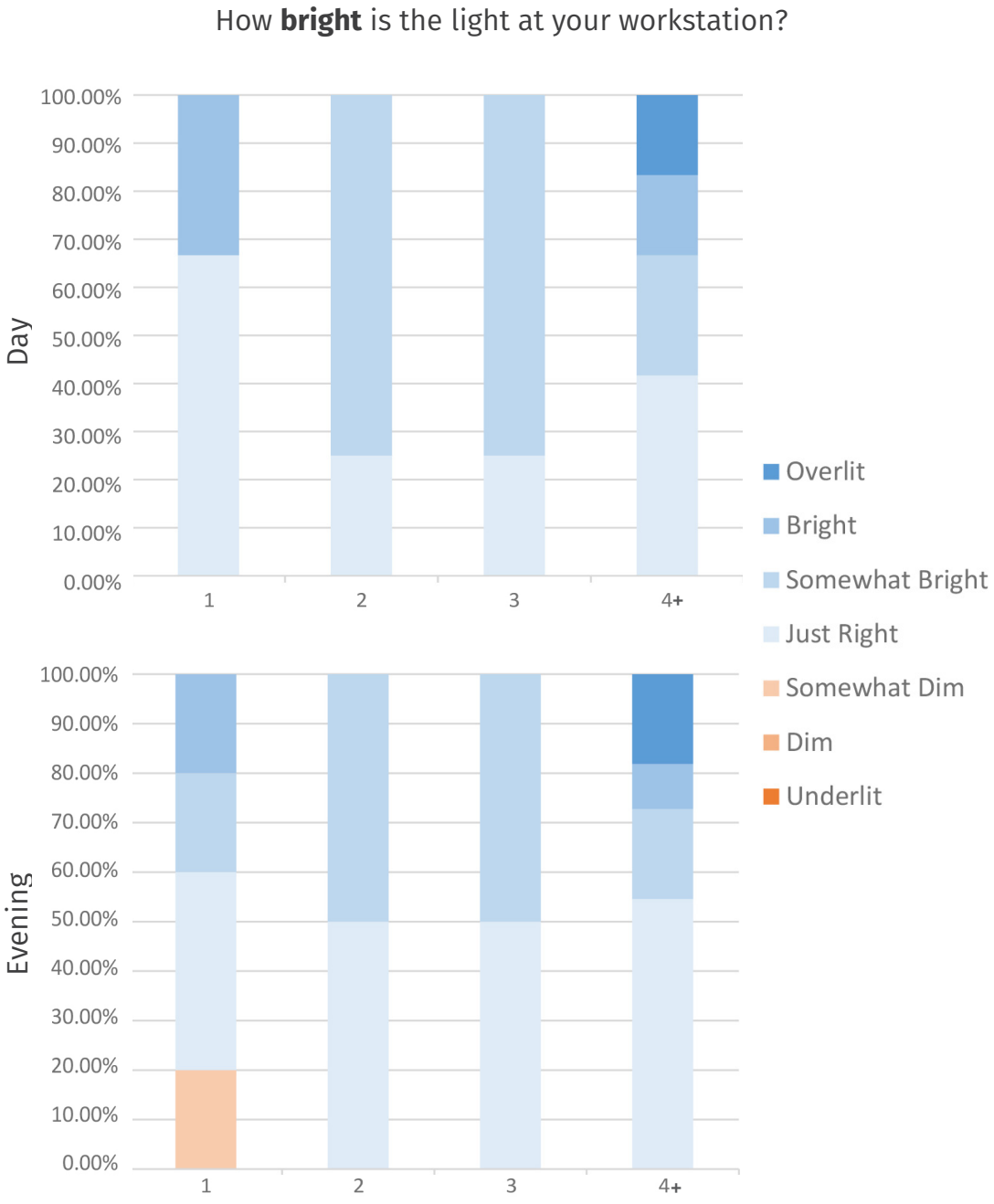


How **comfortable** is the light at your workstation?

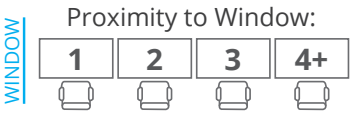


Case Study 3 - UW Tower (levels O-3 and C-3) - 21 Responses

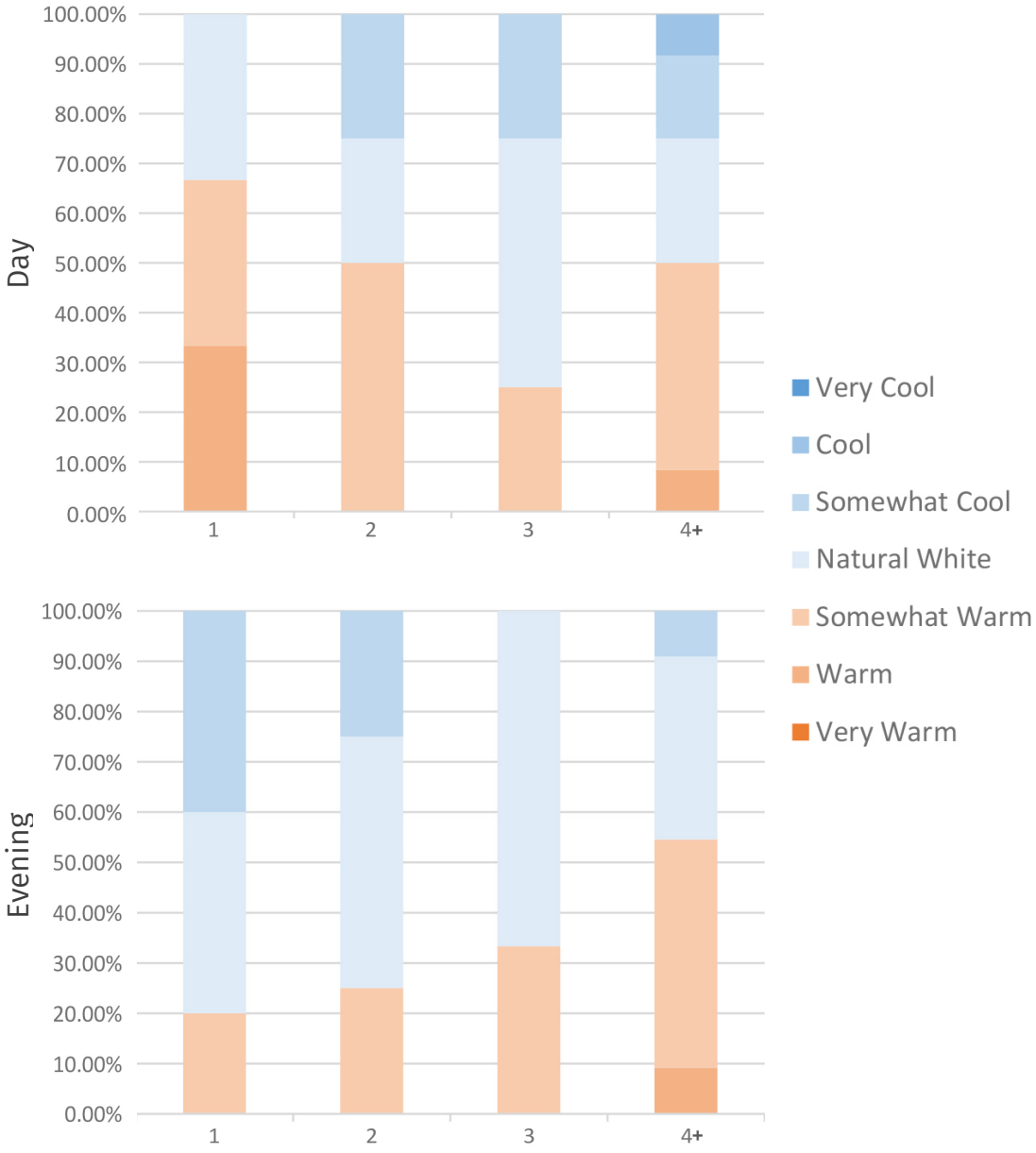




Case Study 3 - UW Tower (levels O-3 and C-3) - 21 Responses



What **color** is the light at your workstation?

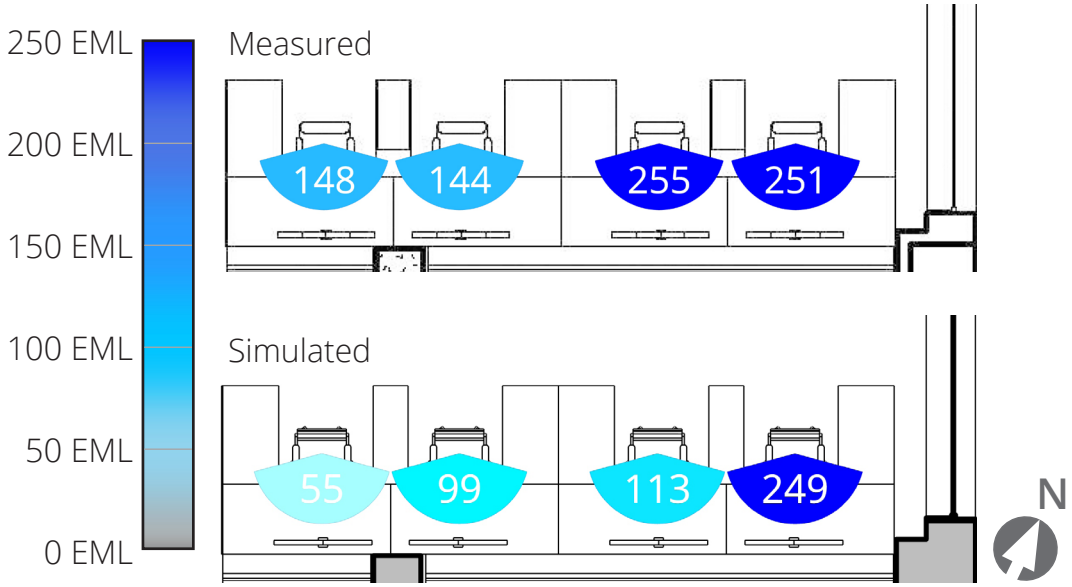


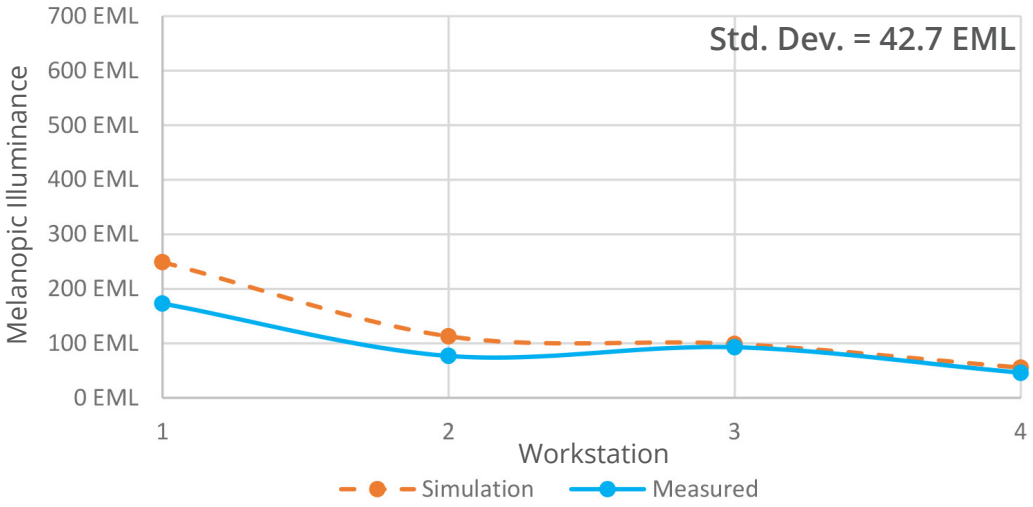
Appendix C: Simulation Analysis Results

Simulation Validation Results - Study 1.1 Comparison - Zone A

Date: Saturday, March 30th
Weather: Clear

Melanopic Illuminance

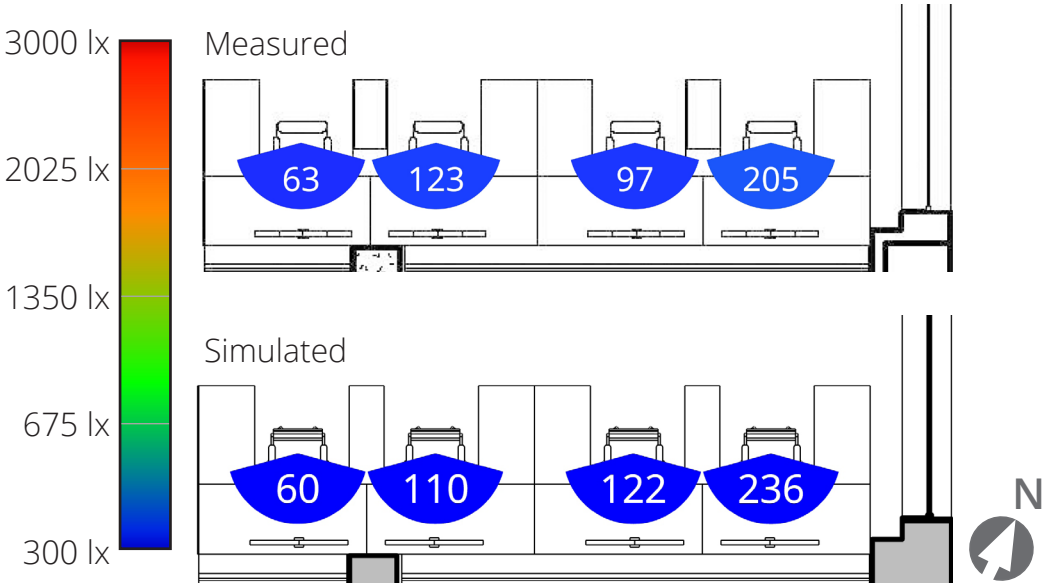


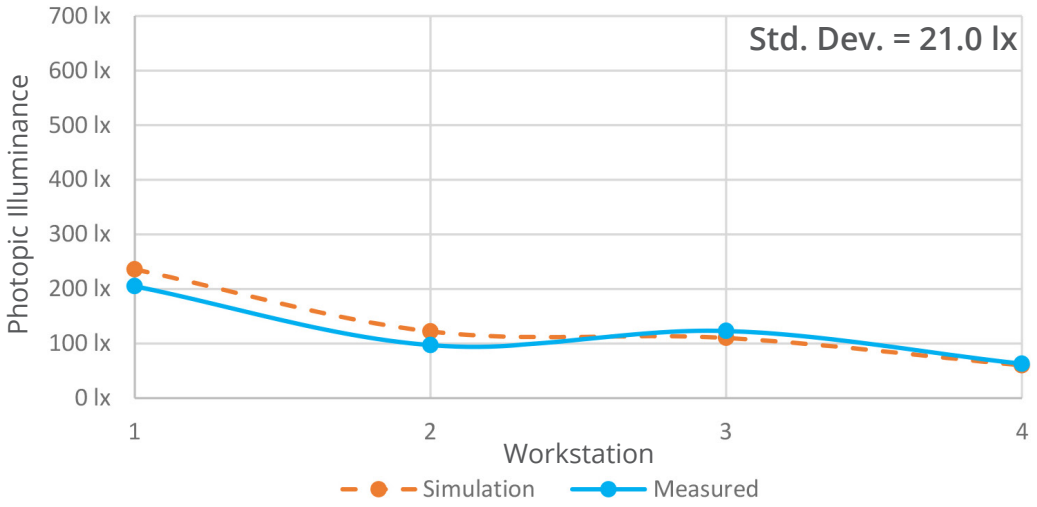


Simulation Validation Results - Study 1.1 Comparison - Zone A

Date: Saturday, March 30th
Weather: Clear

Photopic Illuminance

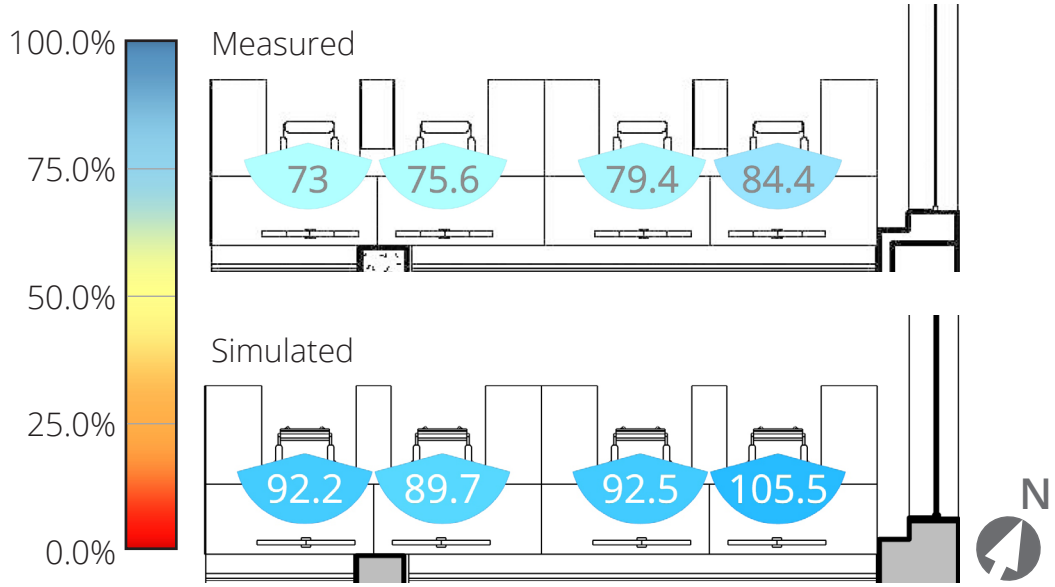


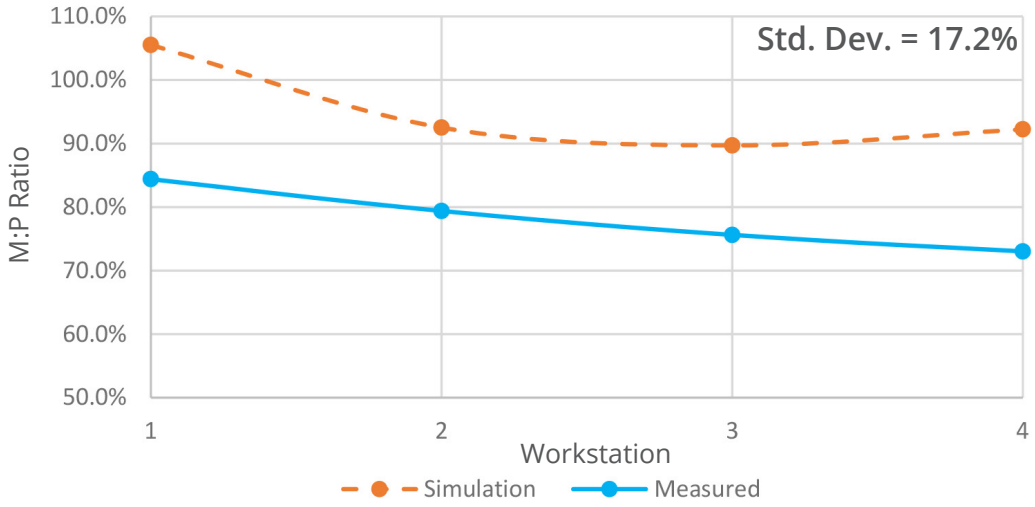


Simulation Validation Results - Study 1.1 Comparison - Zone A

Date: Saturday, March 30th
Weather: Clear

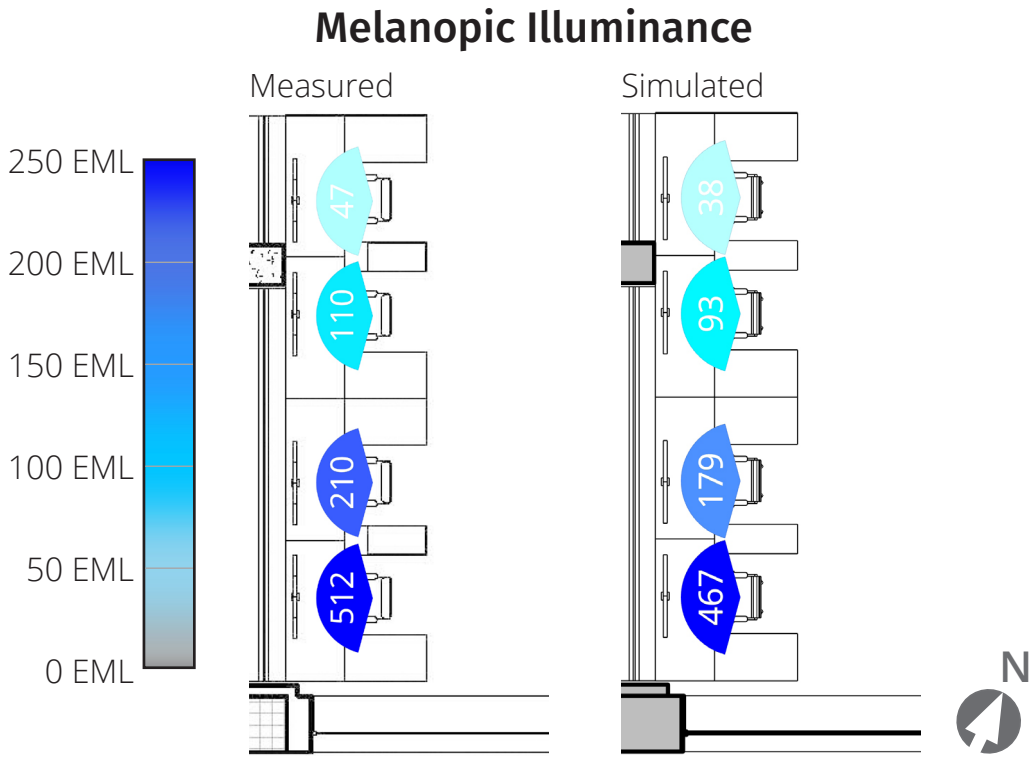
Melanopic : Photopic Ratio

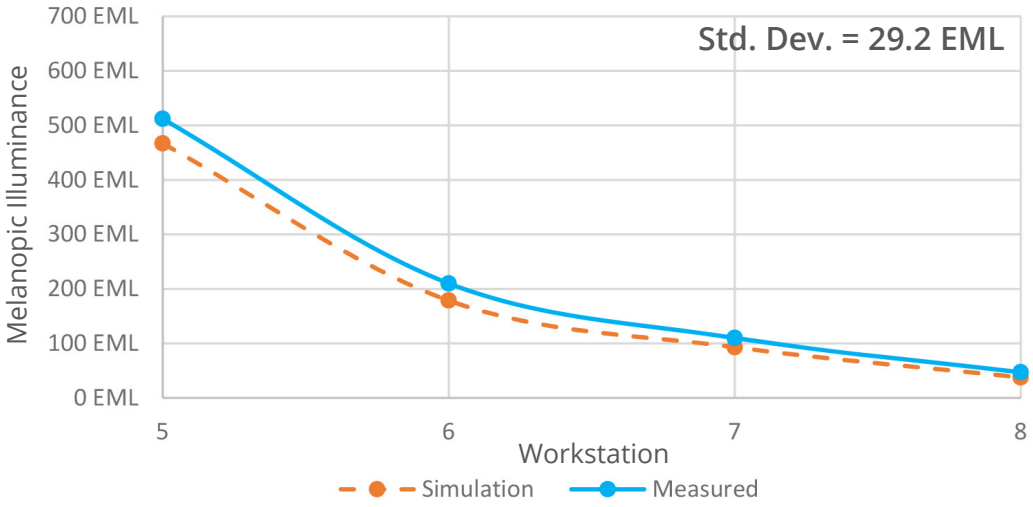




Simulation Validation Results - Study 1.1 Comparison - Zone B

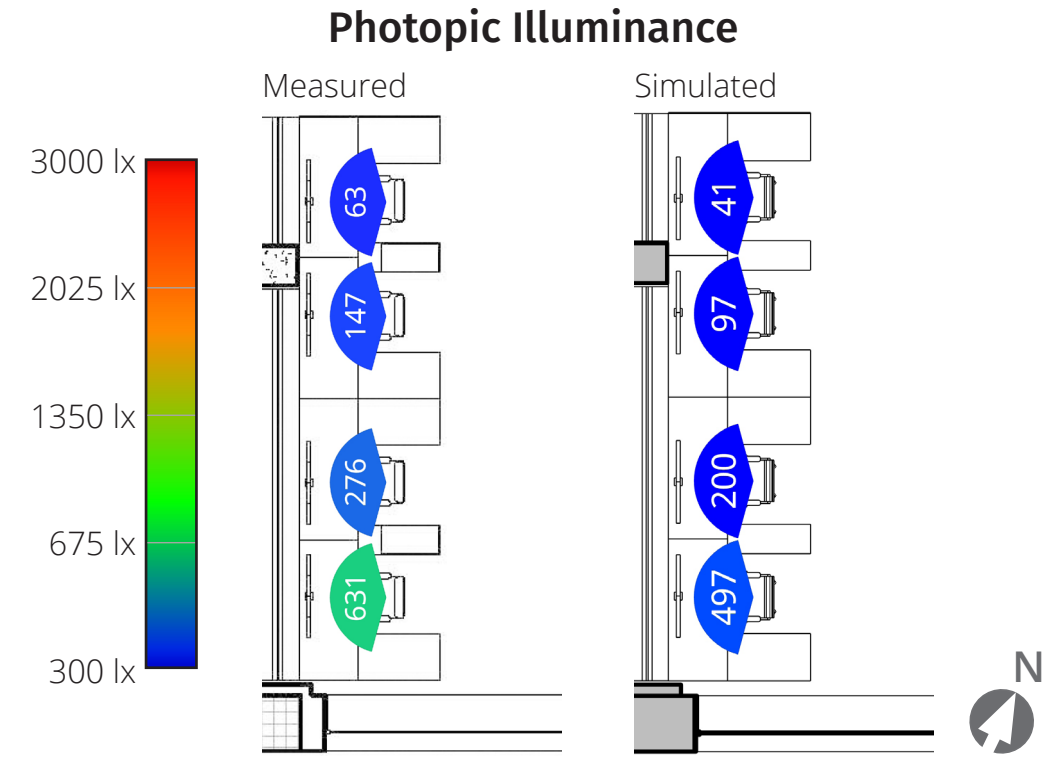
Date: Saturday, March 30th
Weather: Clear

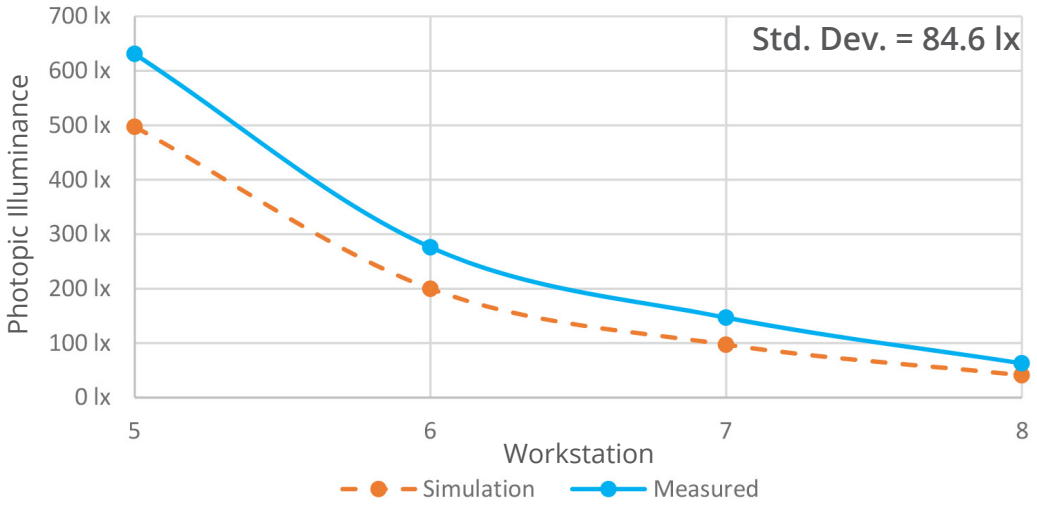




Simulation Validation Results - Study 1.1 Comparison - Zone B

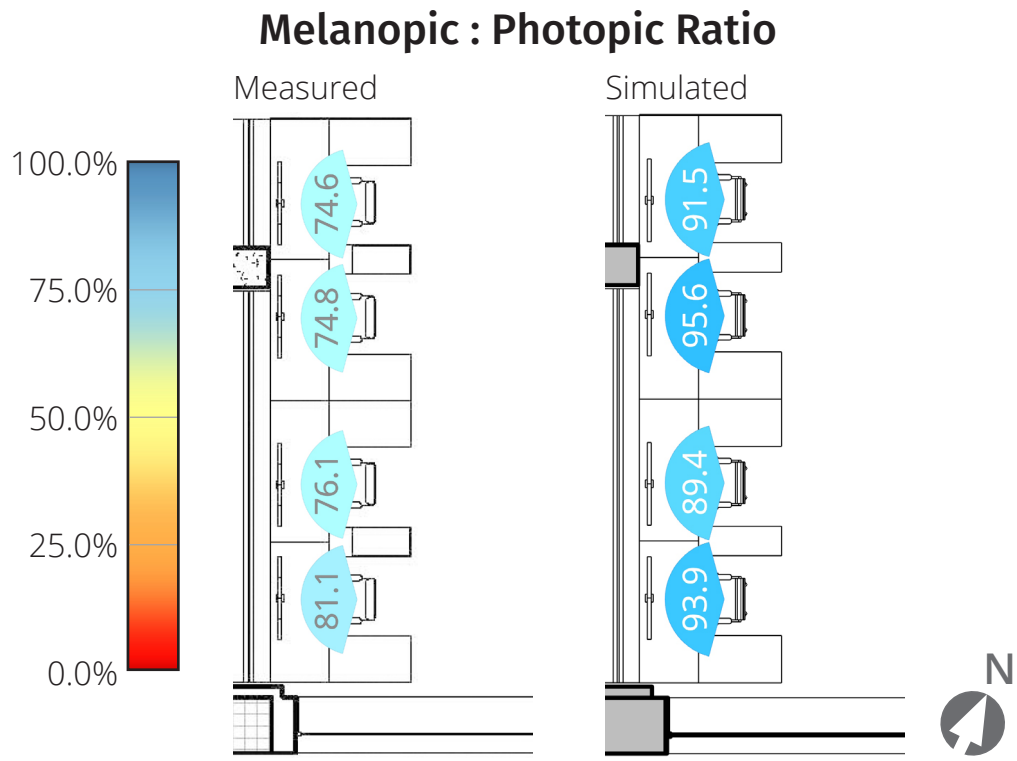
Date: Saturday, March 30th
Weather: Clear

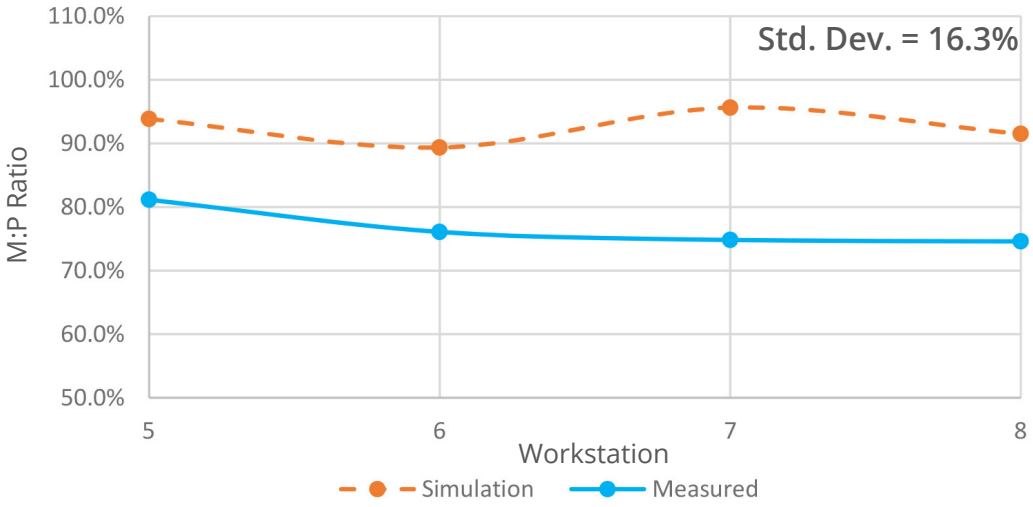




Simulation Validation Results - Study 1.1 Comparison - Zone B

Date: Saturday, March 30th
Weather: Clear

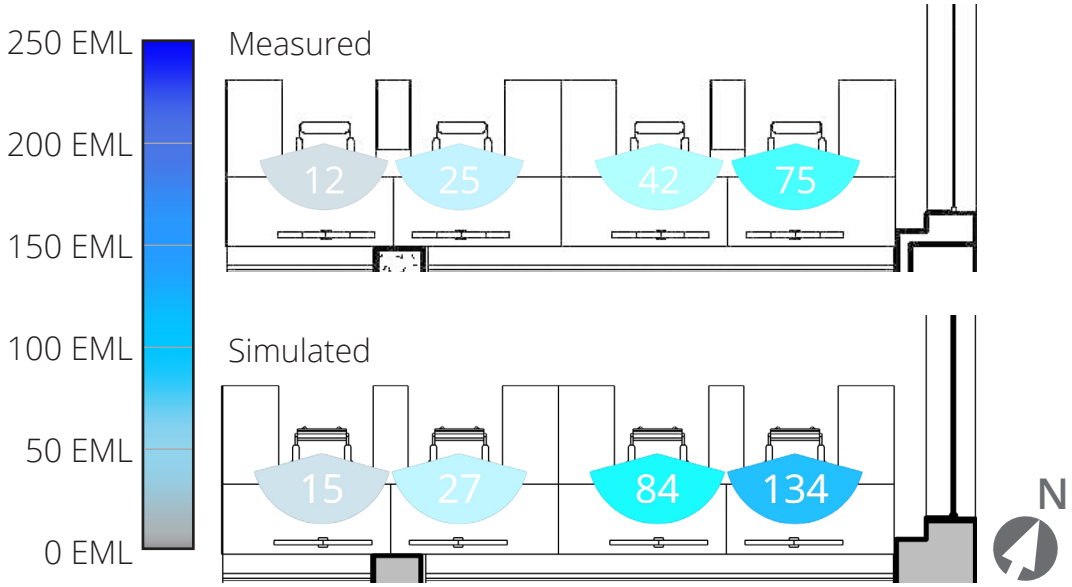


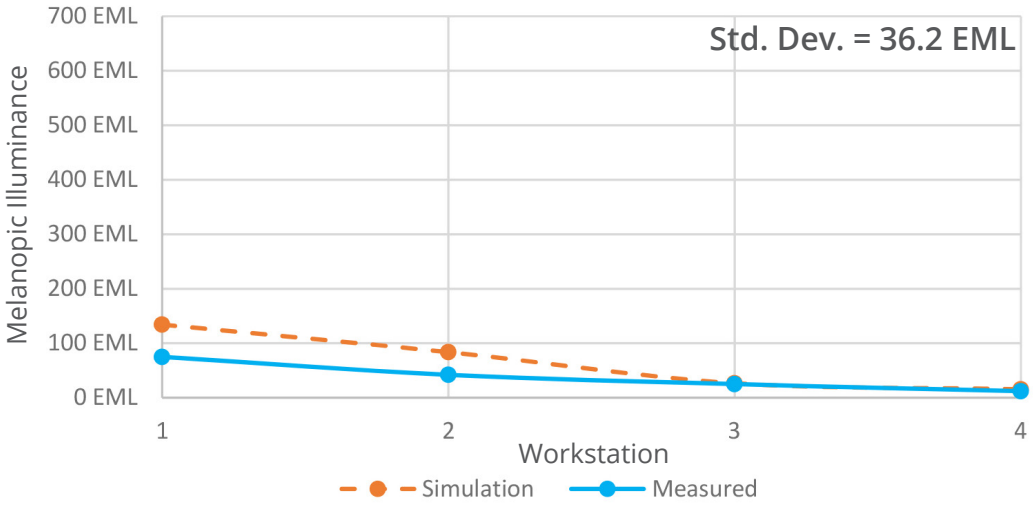


Simulation Validation Results - Study 1.2 Comparison - Zone A

Date: Saturday, March 30th
Weather: Clear

Melanopic Illuminance

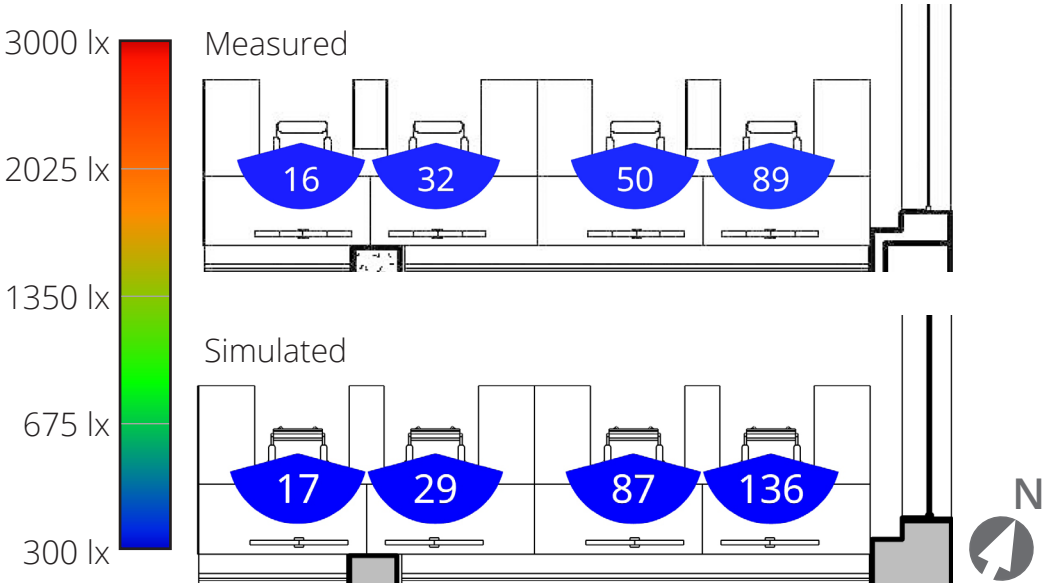


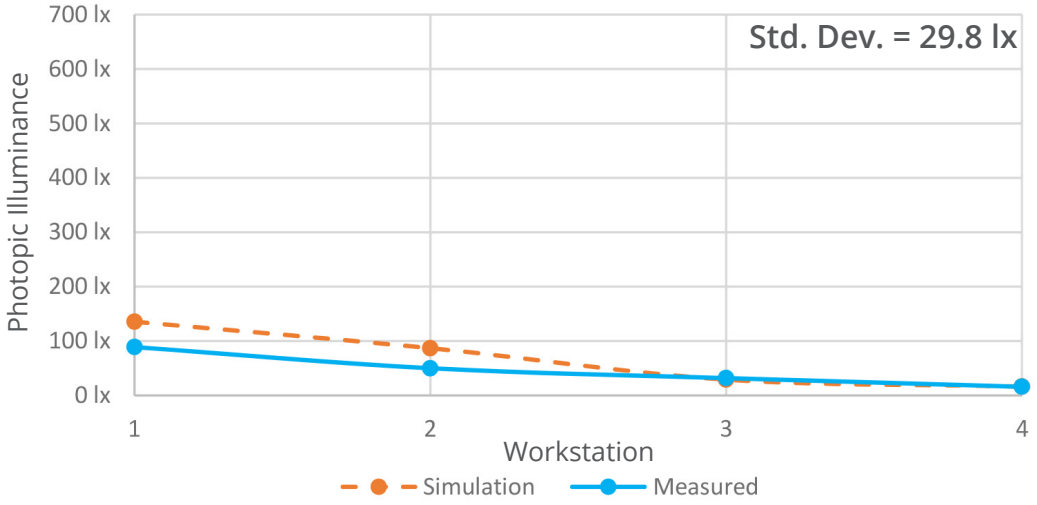


Simulation Validation Results - Study 1.2 Comparison - Zone A

Date: Saturday, March 30th
Weather: Clear

Photopic Illuminance

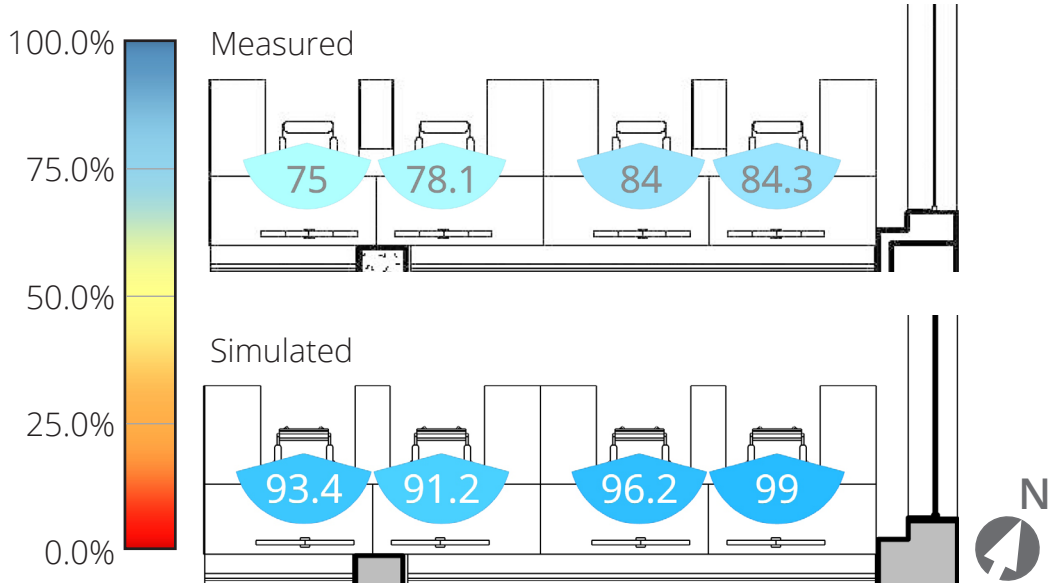


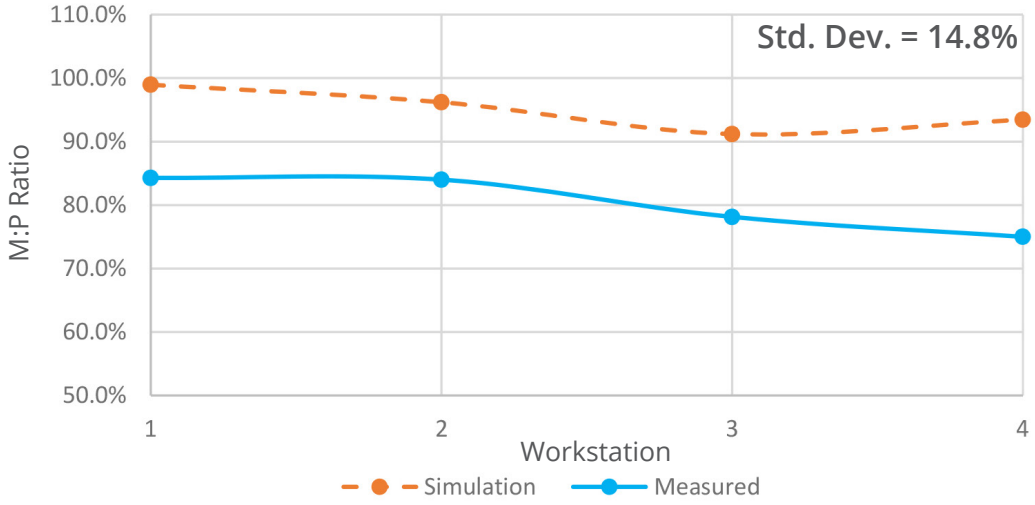


Simulation Validation Results - Study 1.2 Comparison - Zone A

Date: Saturday, March 30th
Weather: Clear

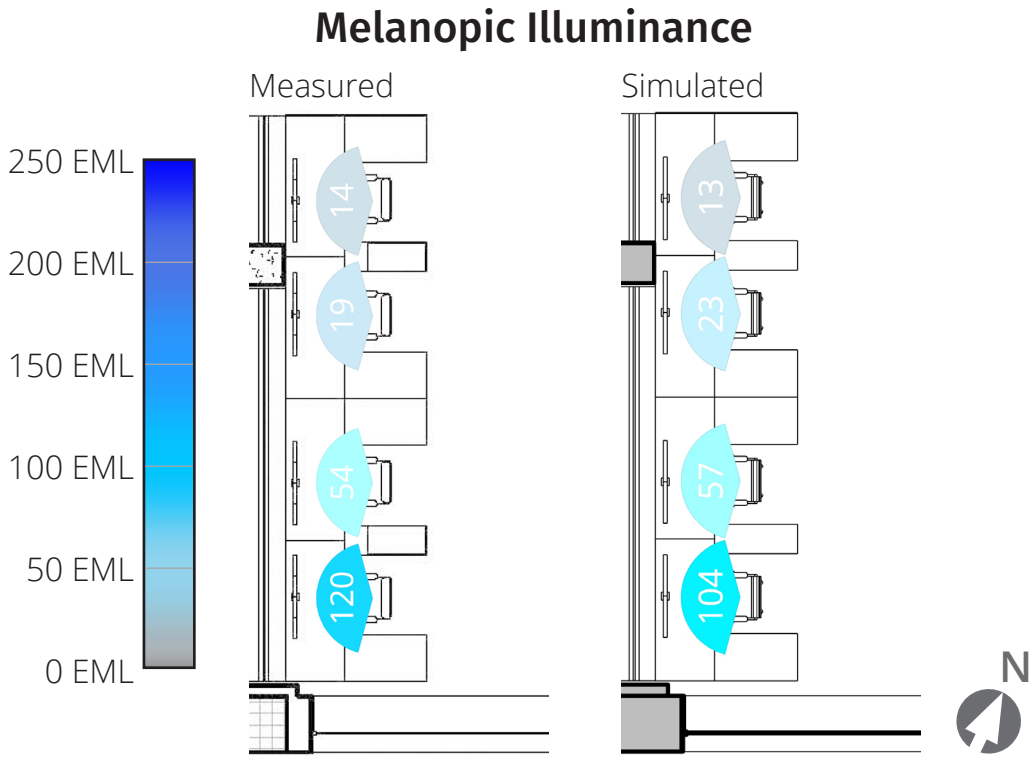
Melanopic : Photopic Ratio

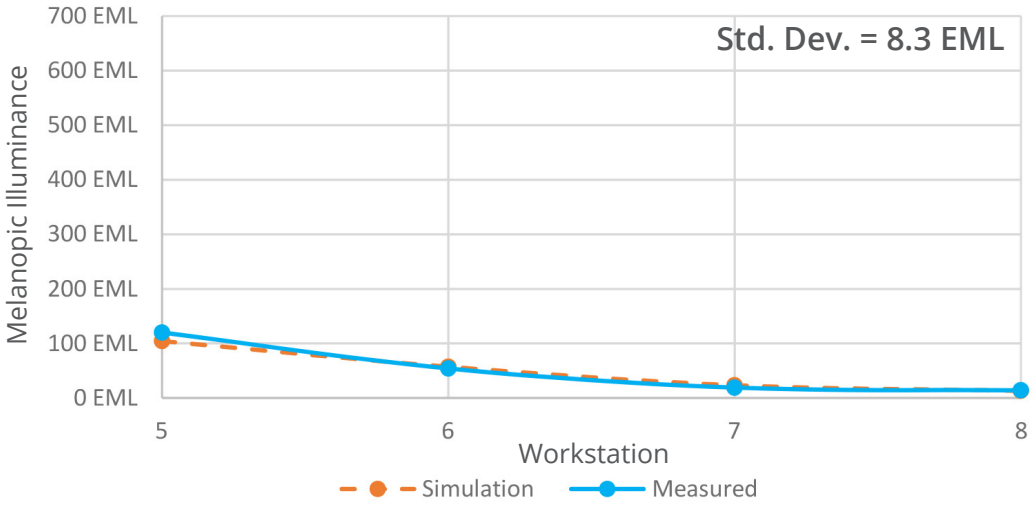




Simulation Validation Results - Study 1.2 Comparison - Zone B

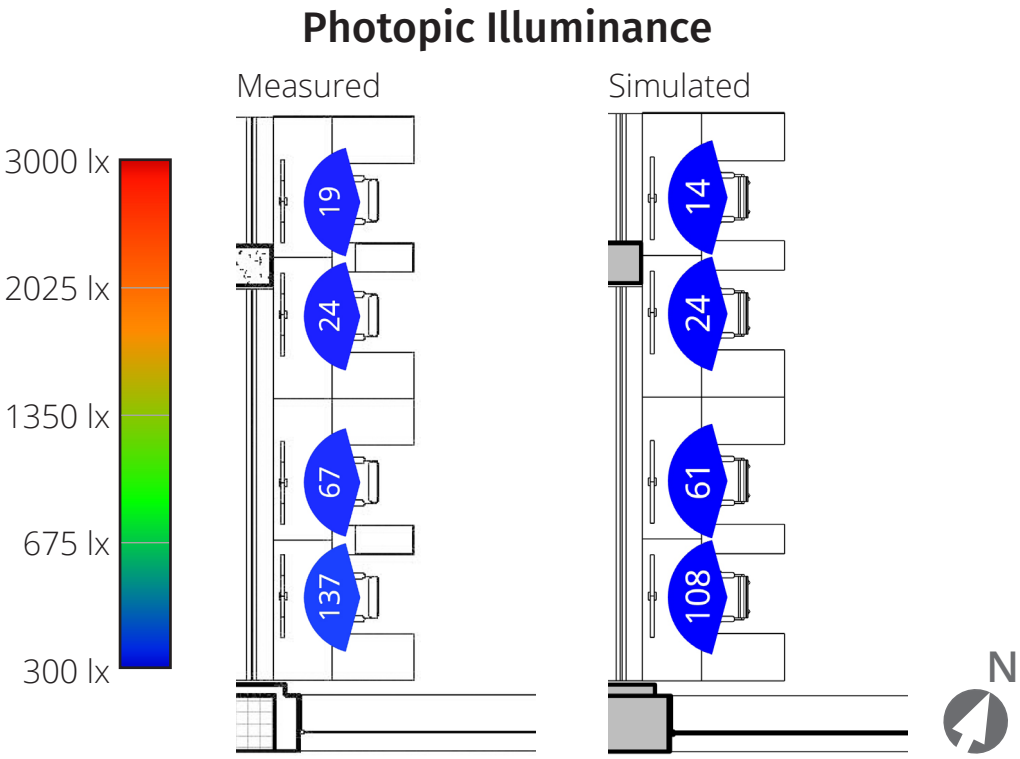
Date: Saturday, March 30th
Weather: Clear

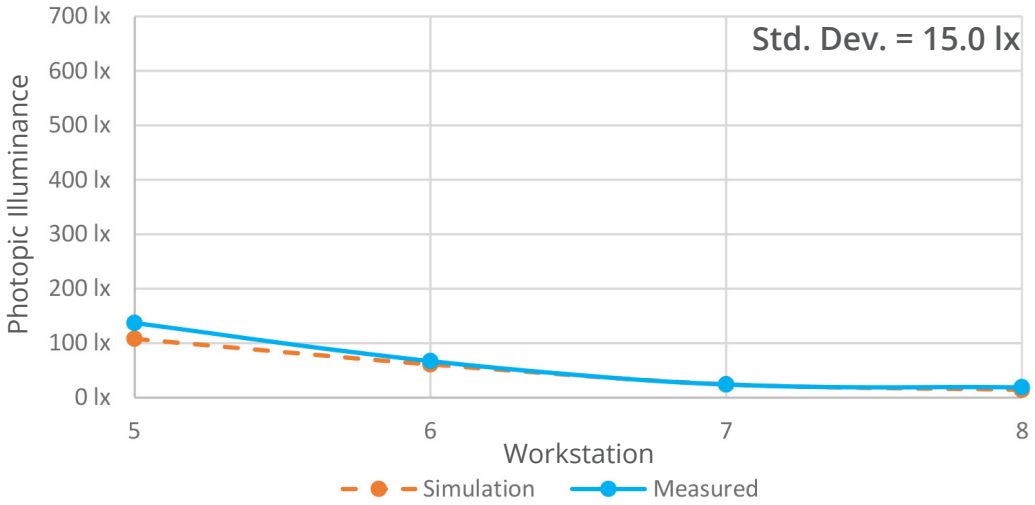




Simulation Validation Results - Study 1.2 Comparison - Zone B

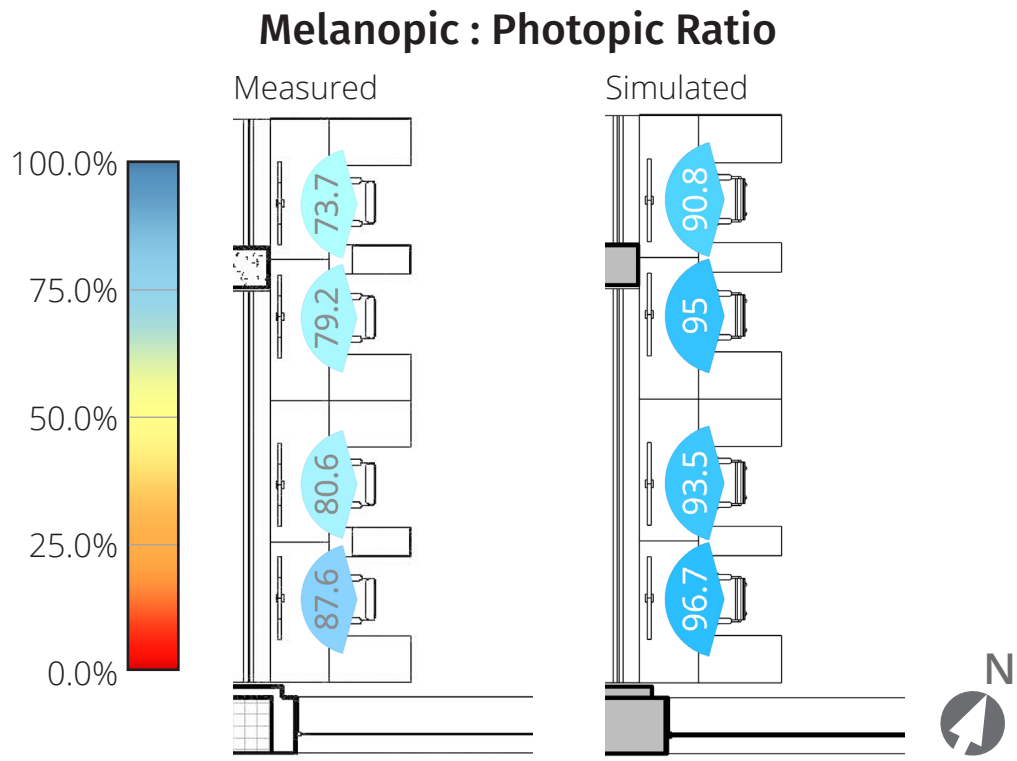
Date: Saturday, March 30th
Weather: Clear

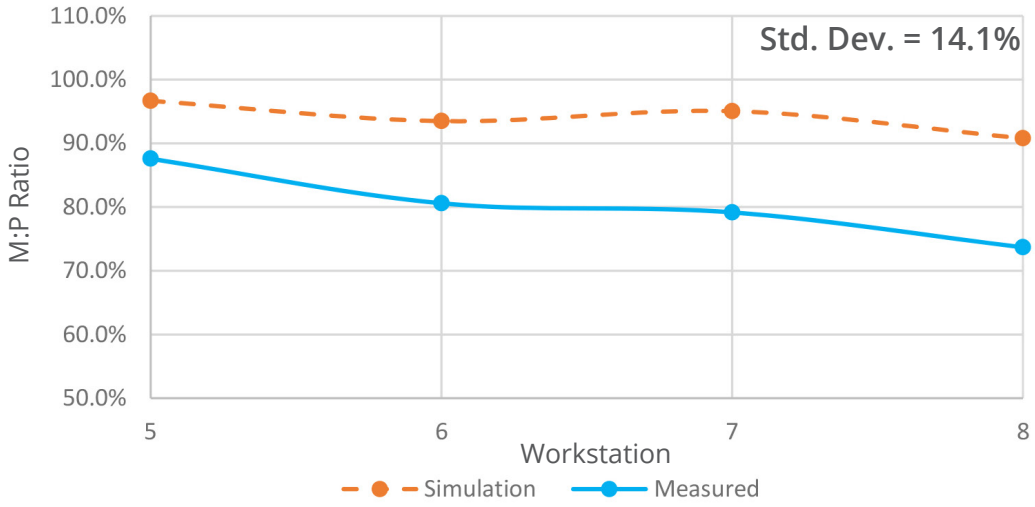




Simulation Validation Results - Study 1.2 Comparison - Zone B

Date: Saturday, March 30th
Weather: Clear

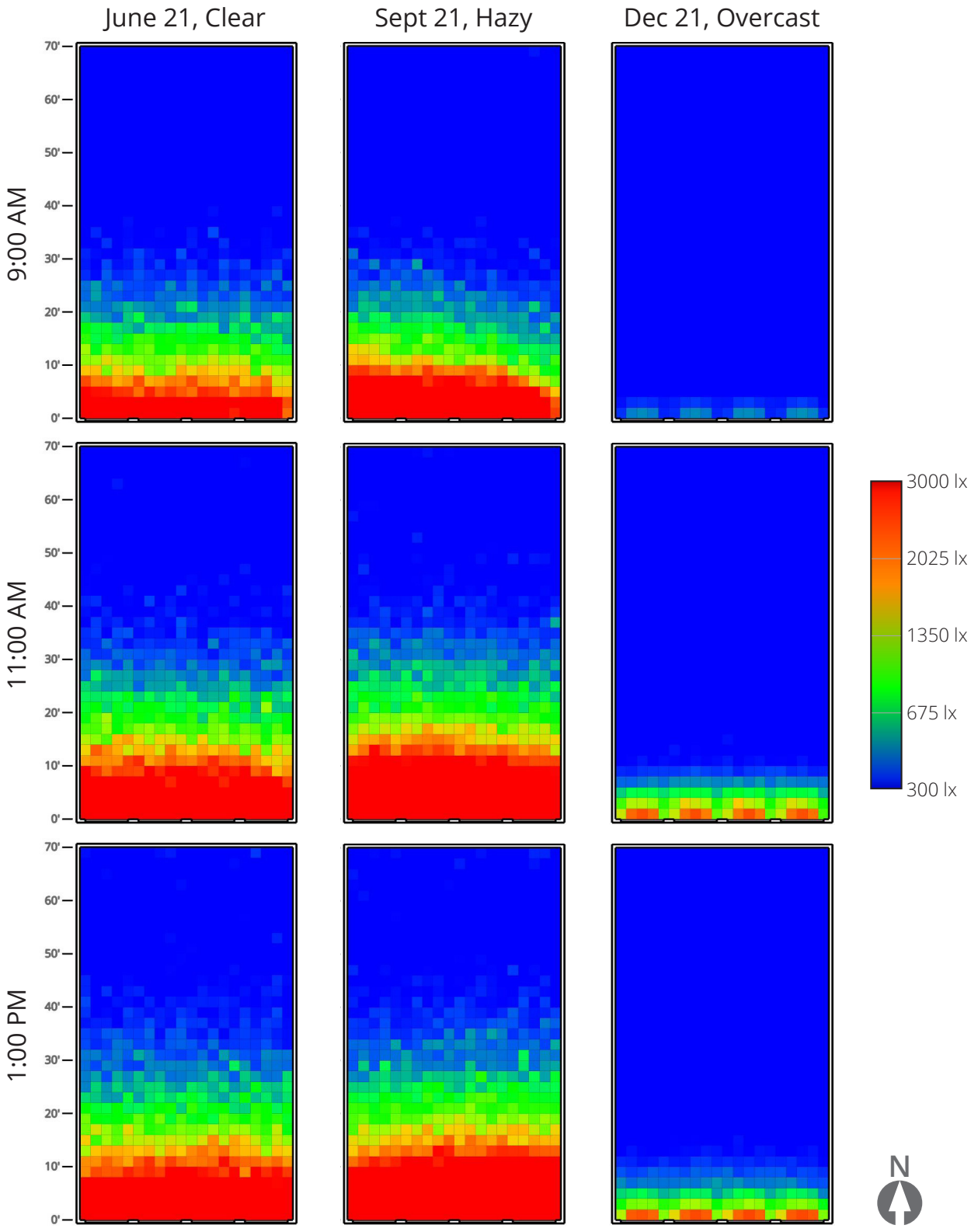




Simulation Control Study - Photopic Illuminance - Workplane Sensors

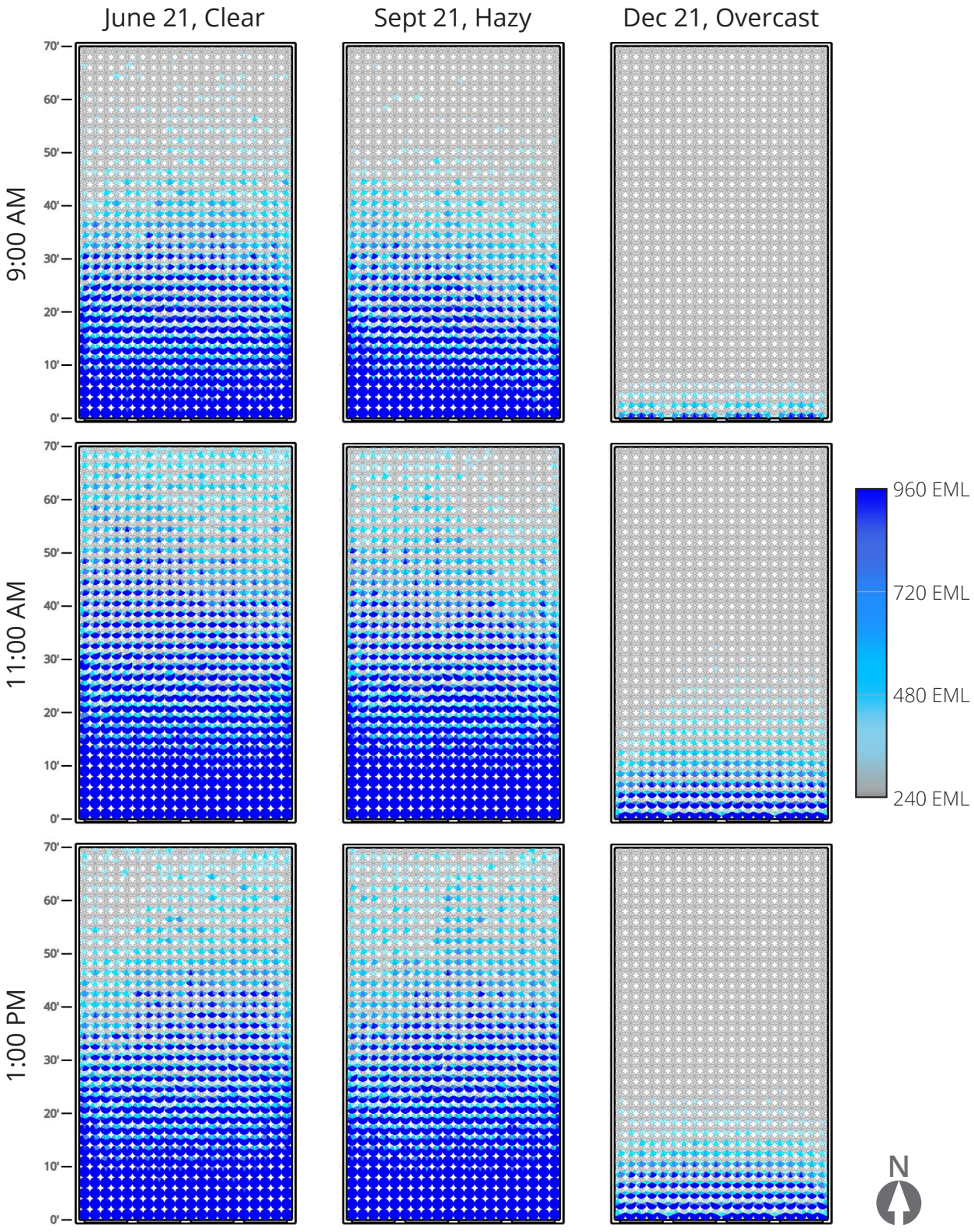
Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: None

Room Depth: 70'-0"
Site Context: None



Simulation Control Study - Melanopic Illuminance - View Sensors

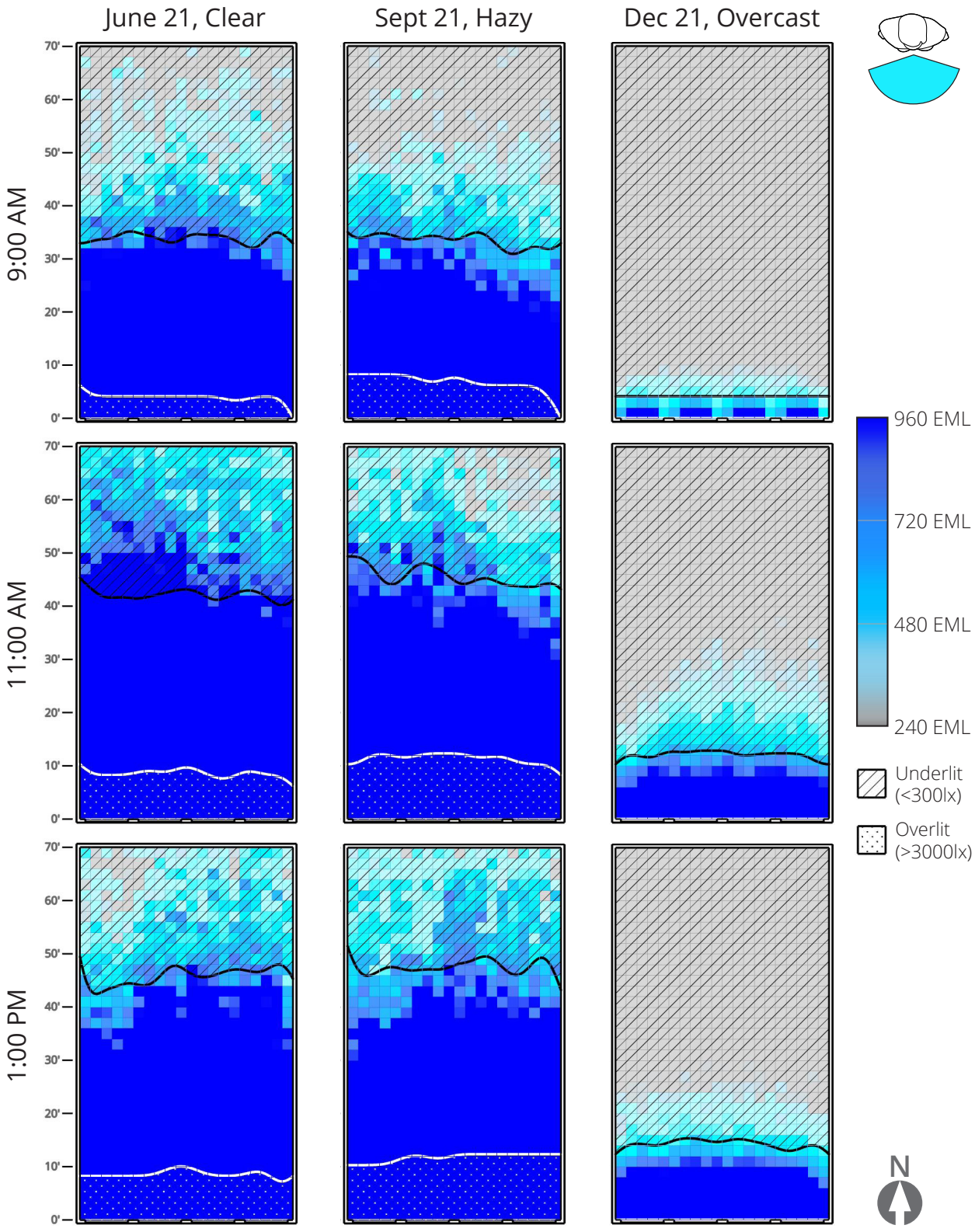
Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: None
Room Depth: 70'-0"
Site Context: None



Simulation Control Study - Melanopic Illuminance - Window Front

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: None

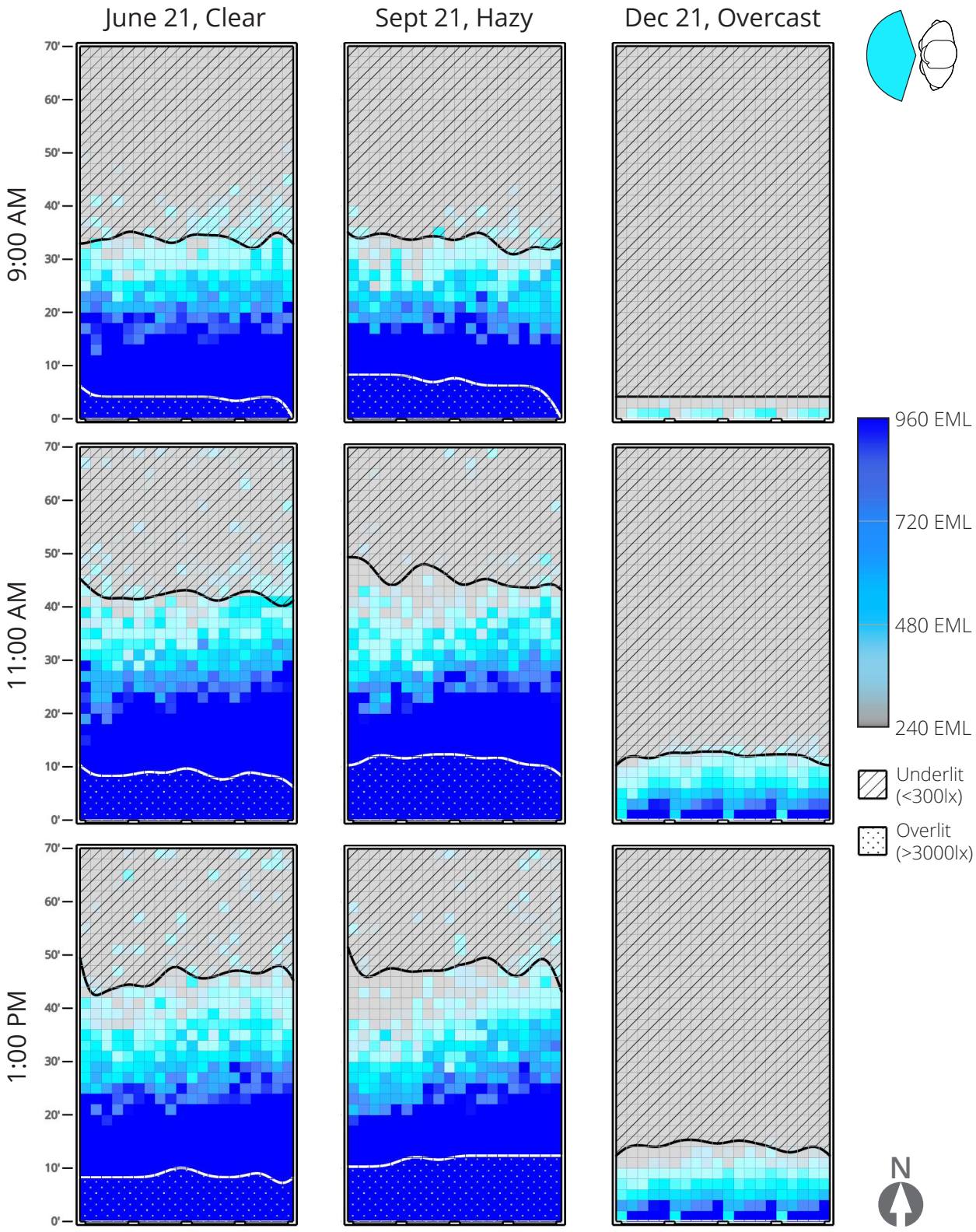
Room Depth: 70'-0"
Site Context: None



Simulation Control Study - Melanopic Illuminance - Window Right

Building Orientation: South
Window Head Height AFF: 8’-0”
Shading Devices: None

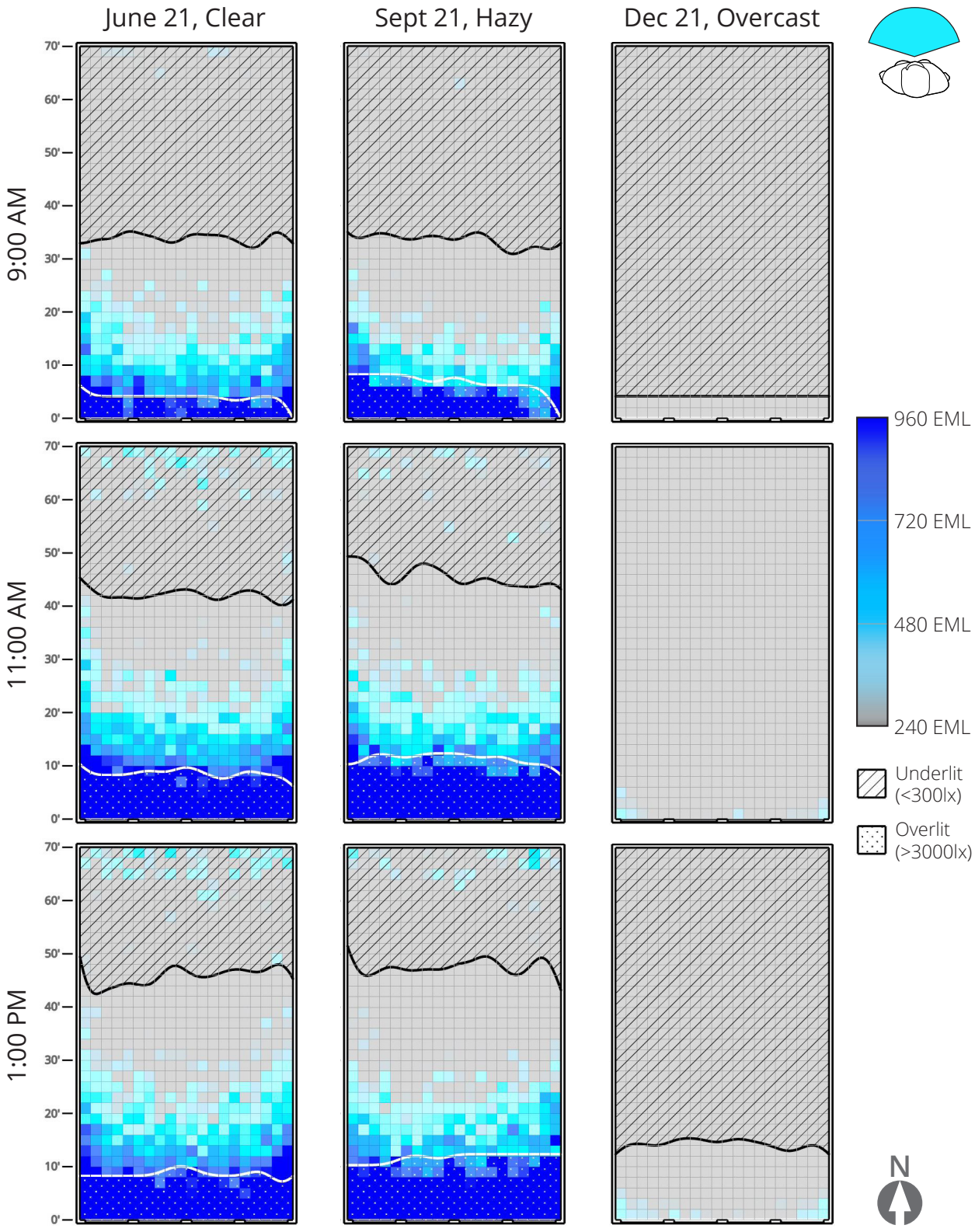
Room Depth: 70’-0”
Site Context: None



Simulation Control Study - Melanopic Illuminance - Window Behind

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: None

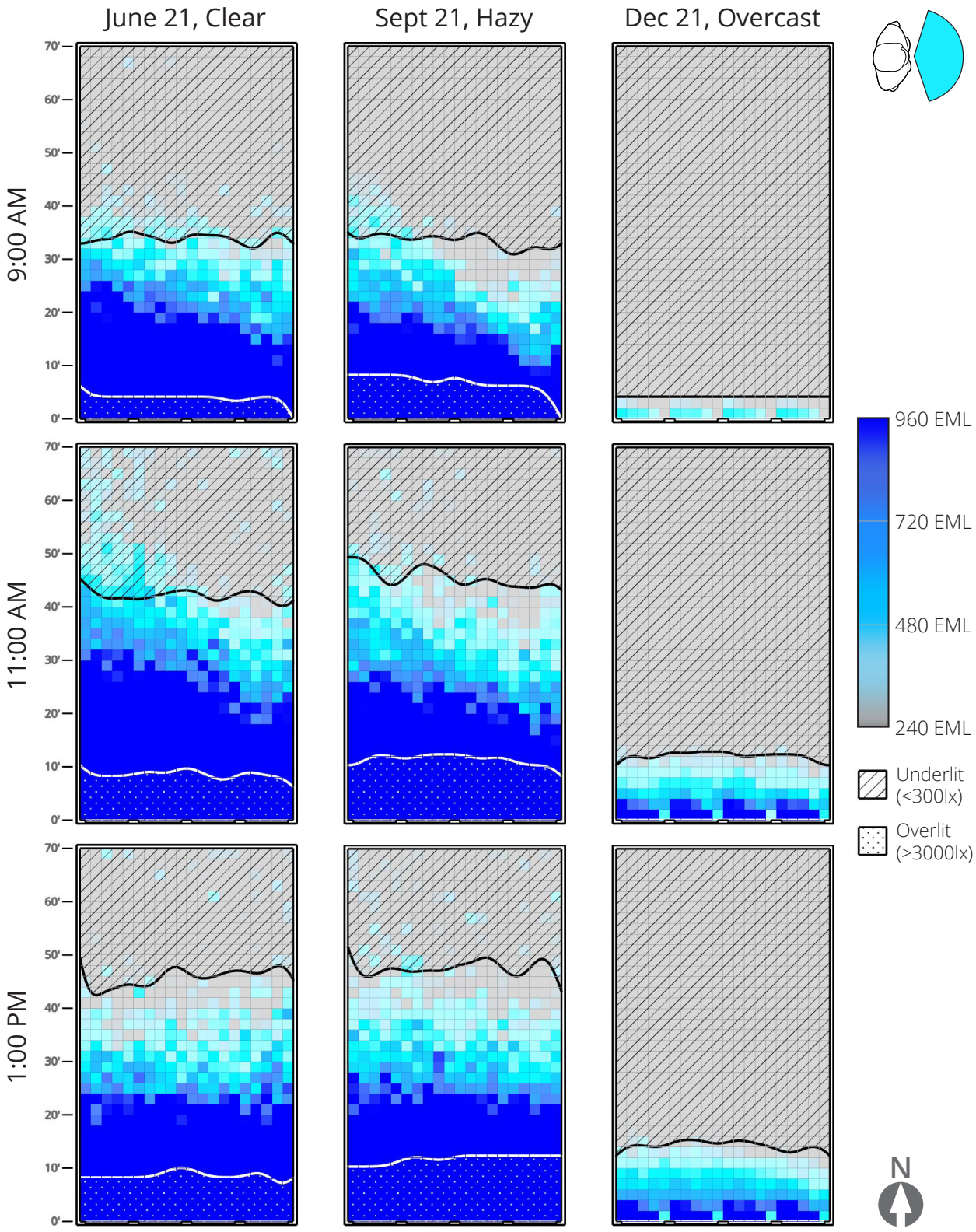
Room Depth: 70'-0"
Site Context: None



Simulation Control Study - Melanopic Illuminance - Window Left

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: None

Room Depth: 70'-0"
Site Context: None

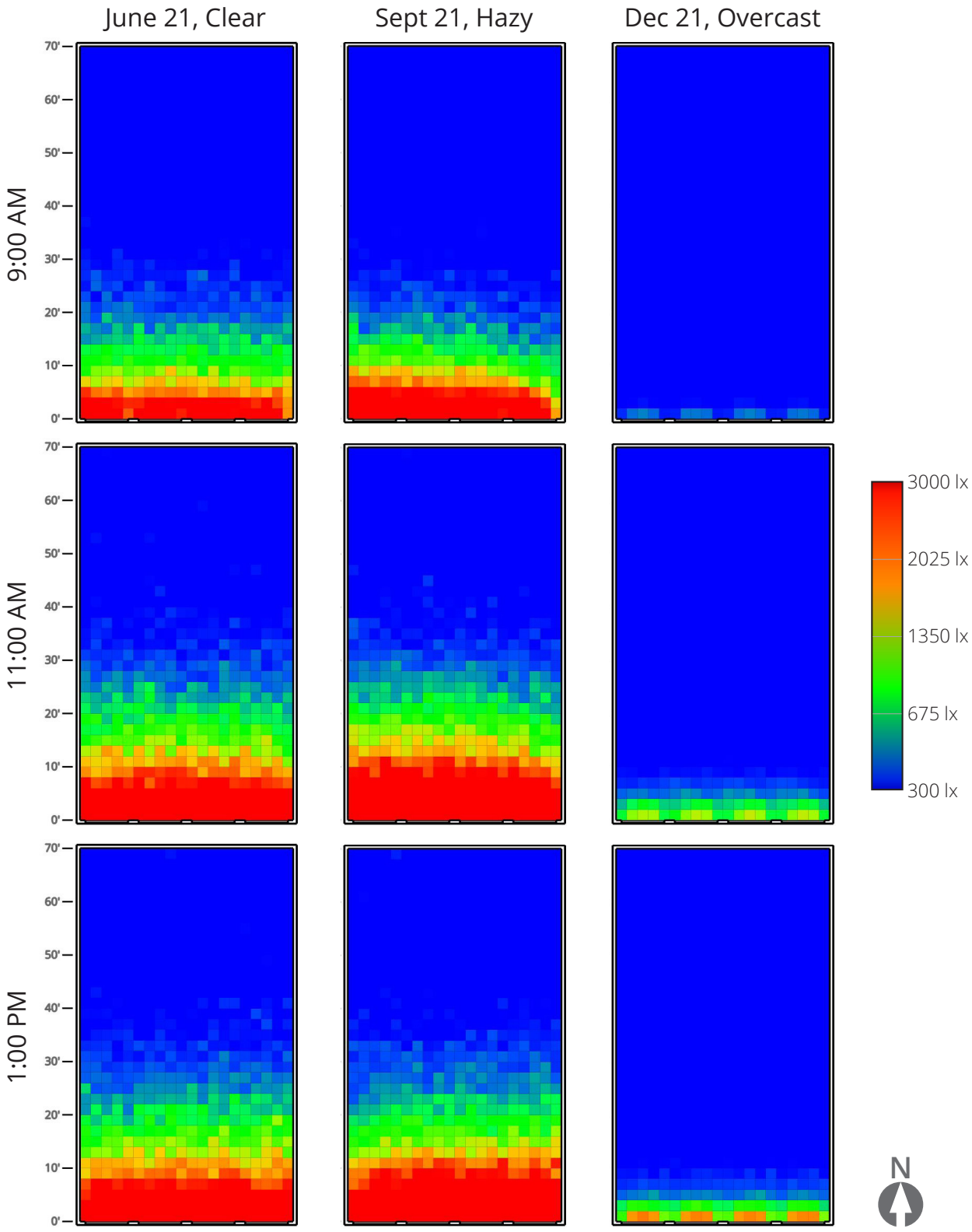


Window Head Height Study - Photopic Illuminance - Workplane Sensors

Building Orientation: South
Window Head Height AFF: 7’-0”
Shading Devices: None

Room Depth: 70’-0”
Site Context: None



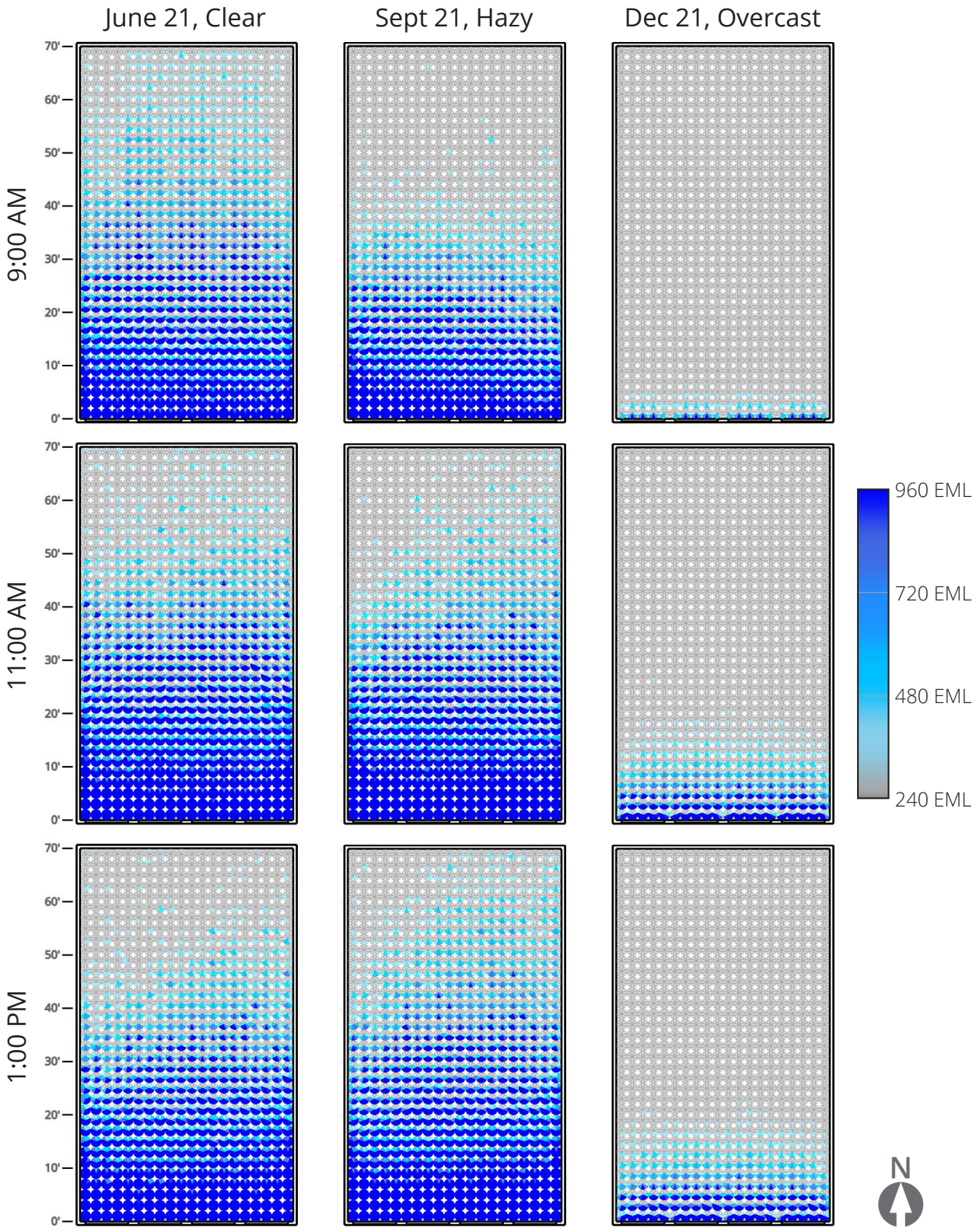


Window Head Height Study - Melanopic Illuminance - View Sensors

Building Orientation: South
Window Head Height AFF: 7’-0”
Shading Devices: None

Room Depth: 70’-0”
Site Context: None

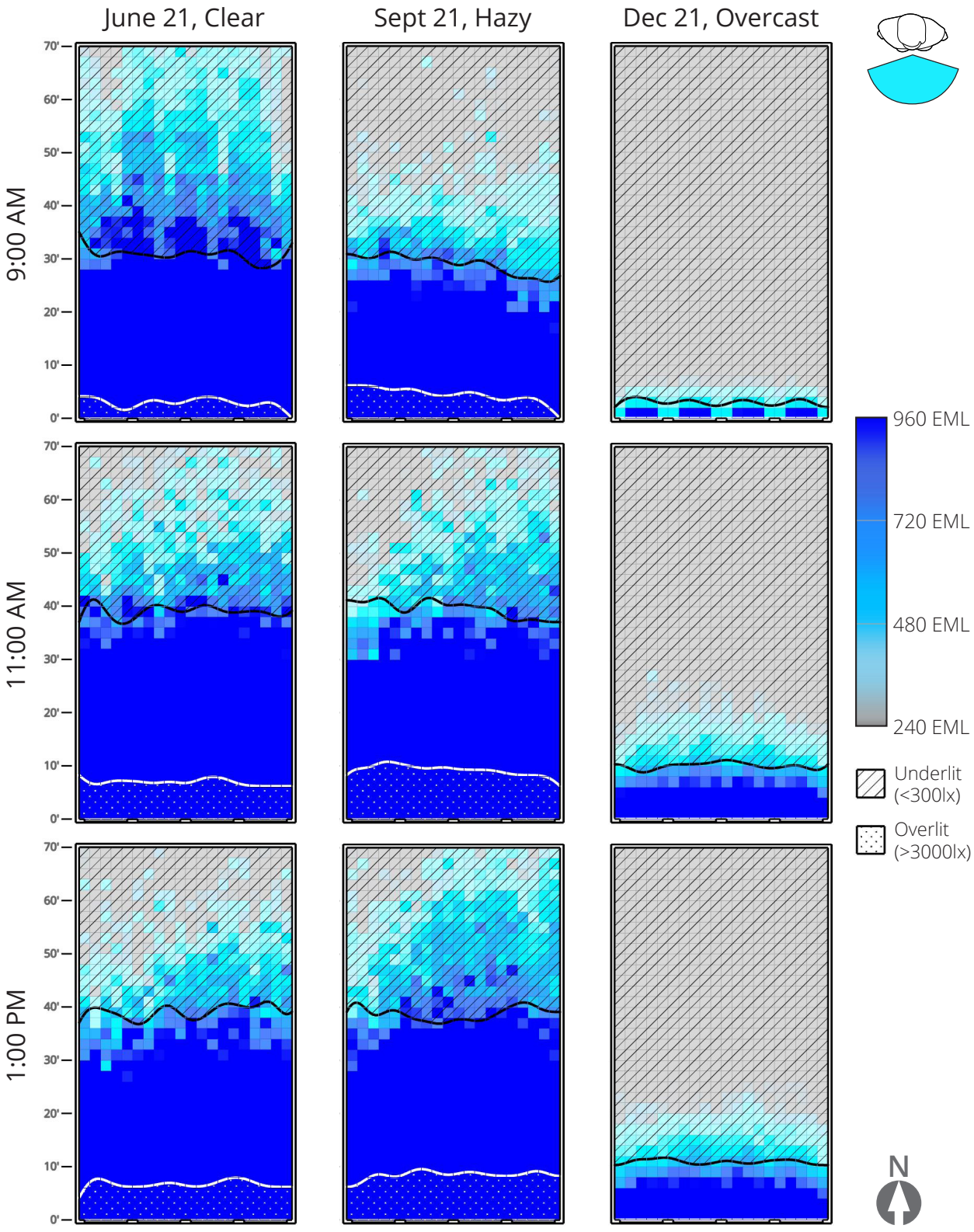




Window Head Height Study - Melanopic Illuminance - Window Front

Building Orientation: South
Window Head Height AFF: 7’-0”
Shading Devices: None

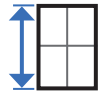
Room Depth: 70’-0”
Site Context: None

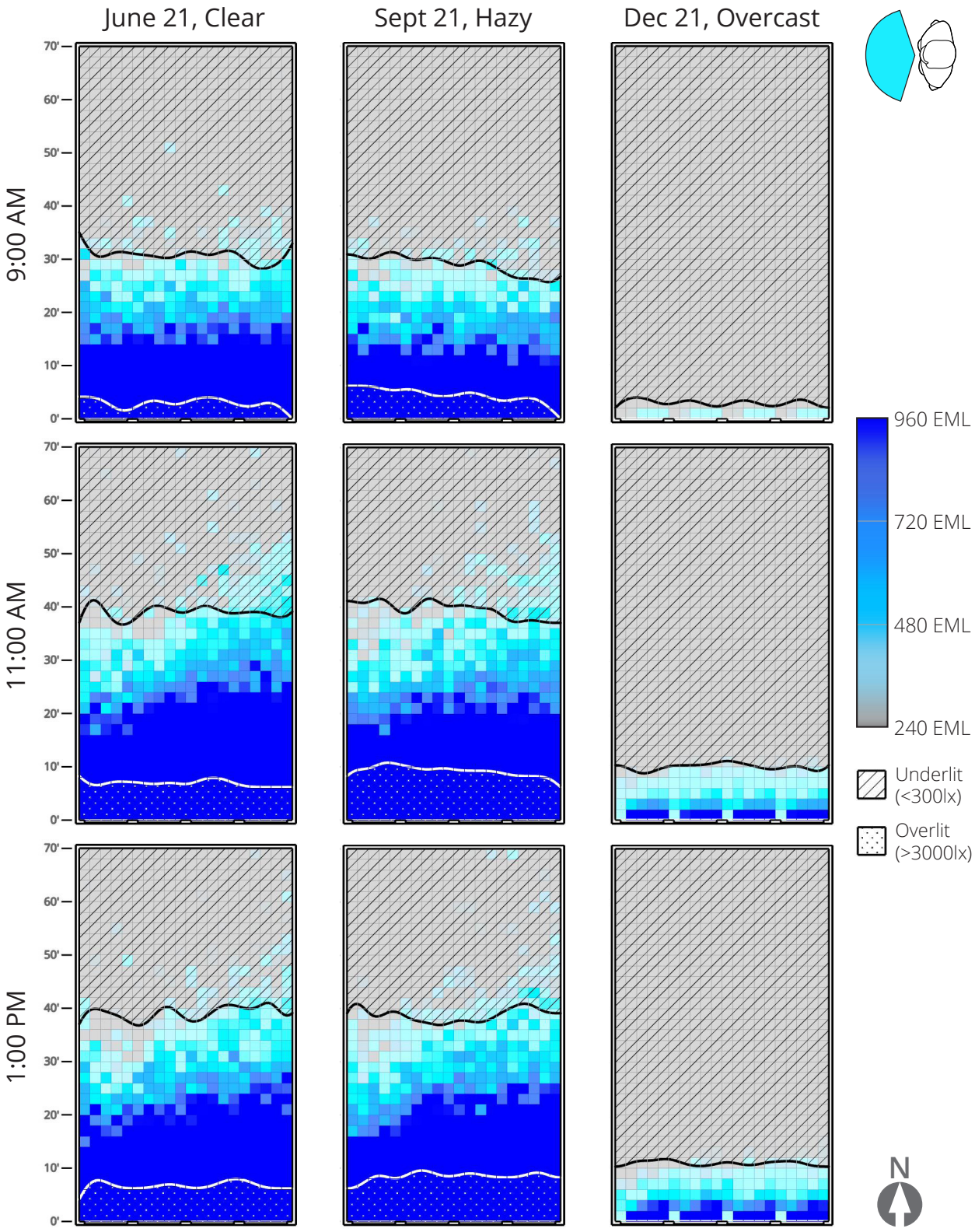


Window Head Height Study - Melanopic Illuminance - Window Right

Building Orientation: South
Window Head Height AFF: 7’-0”
Shading Devices: None

Room Depth: 70’-0”
Site Context: None



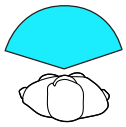


Window Head Height Study - Melanopic Illuminance - Window Behind

Building Orientation: South
Window Head Height AFF: 7’-0”
Shading Devices: None

Room Depth: 70’-0”
Site Context: None



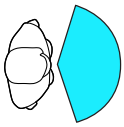


Window Head Height Study - Melanopic Illuminance - Window Left

Building Orientation: South
Window Head Height AFF: 7’-0”
Shading Devices: None

Room Depth: 70’-0”
Site Context: None



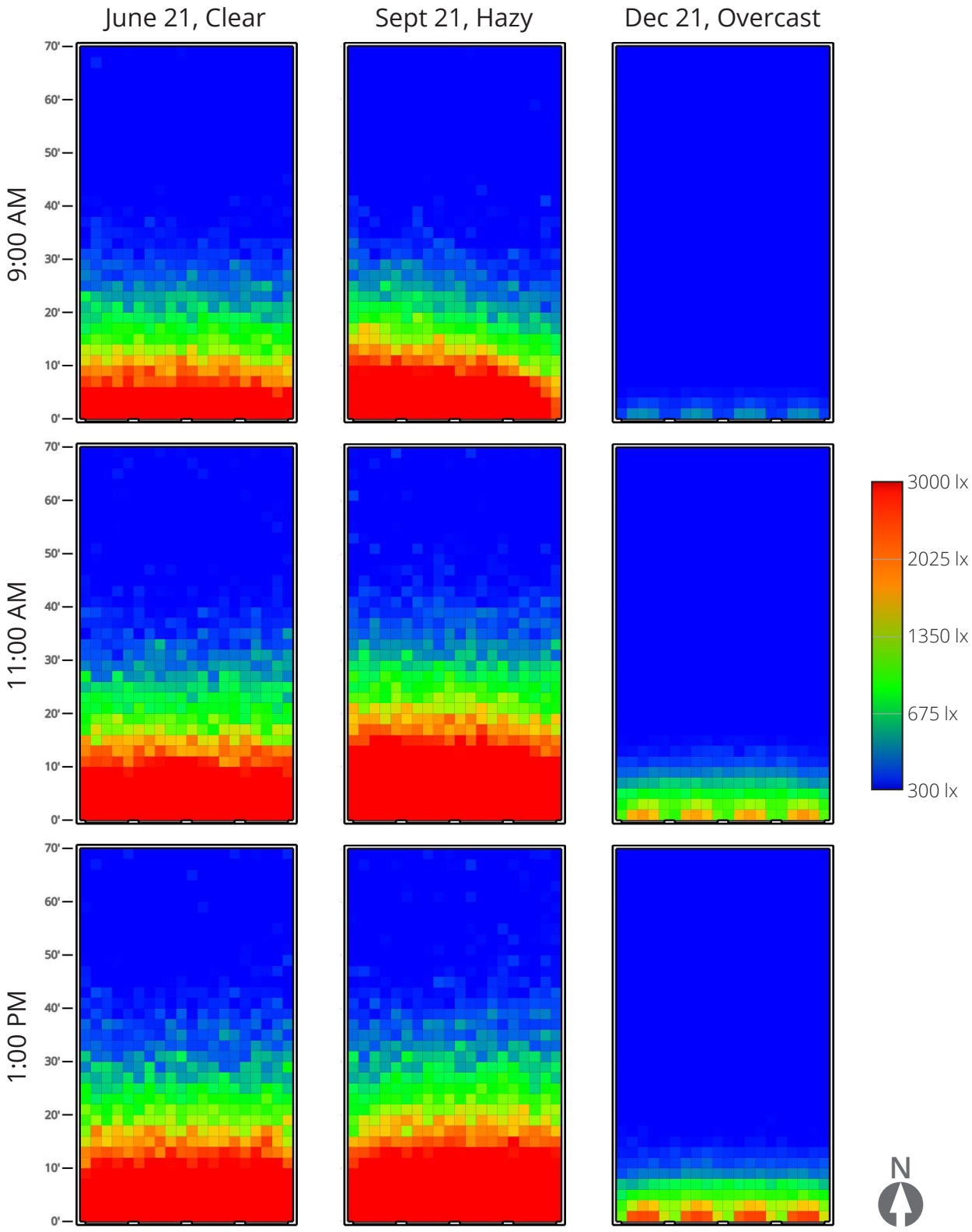


Window Head Height Study - Photopic Illuminance - Workplane Sensors

Building Orientation: South
Window Head Height AFF: 9'-0"
Shading Devices: None

Room Depth: 70'-0"
Site Context: None



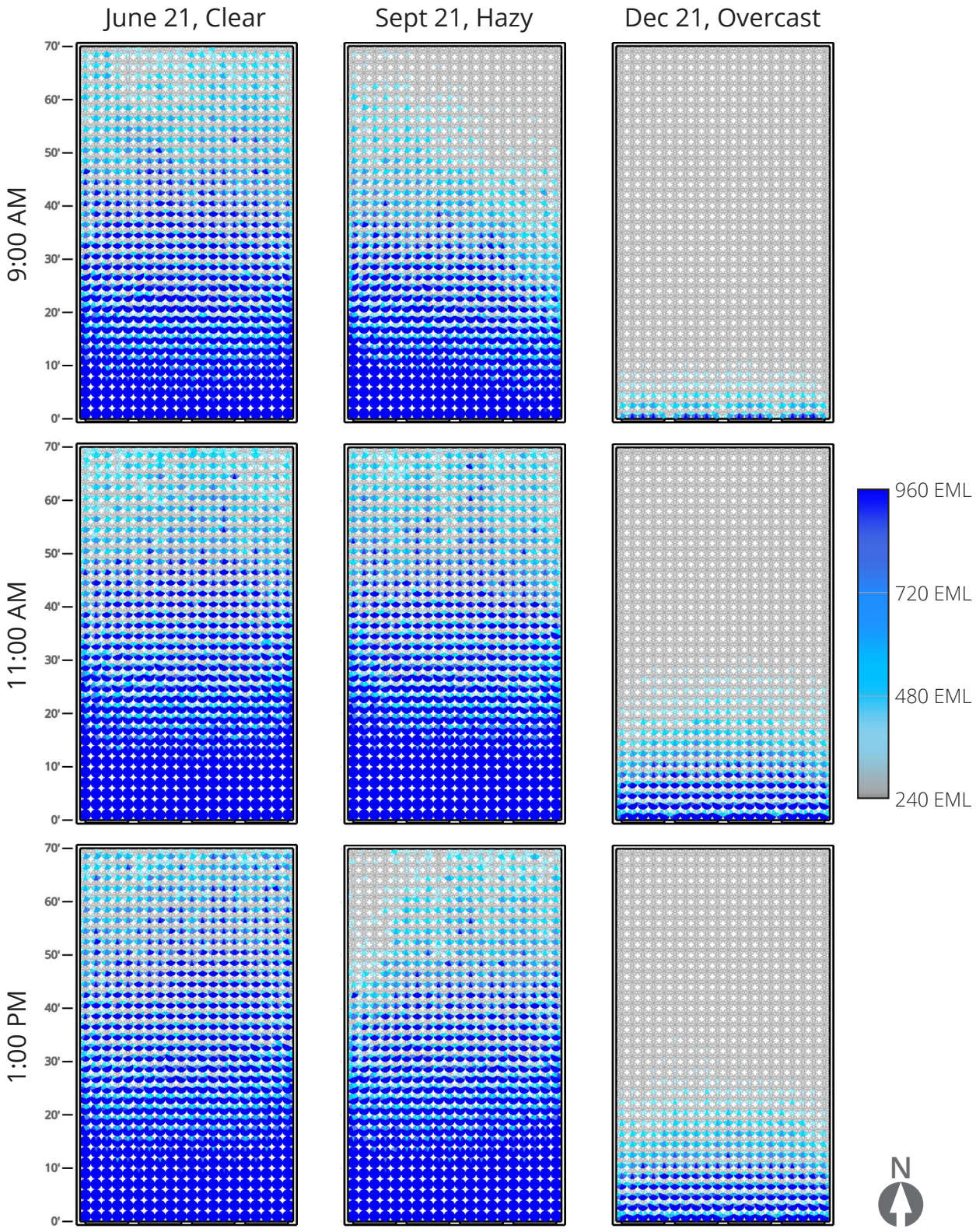


Window Head Height Study - Melanopic Illuminance - View Sensors

Building Orientation: South
Window Head Height AFF: 9'-0"
Shading Devices: None

Room Depth: 70'-0"
Site Context: None

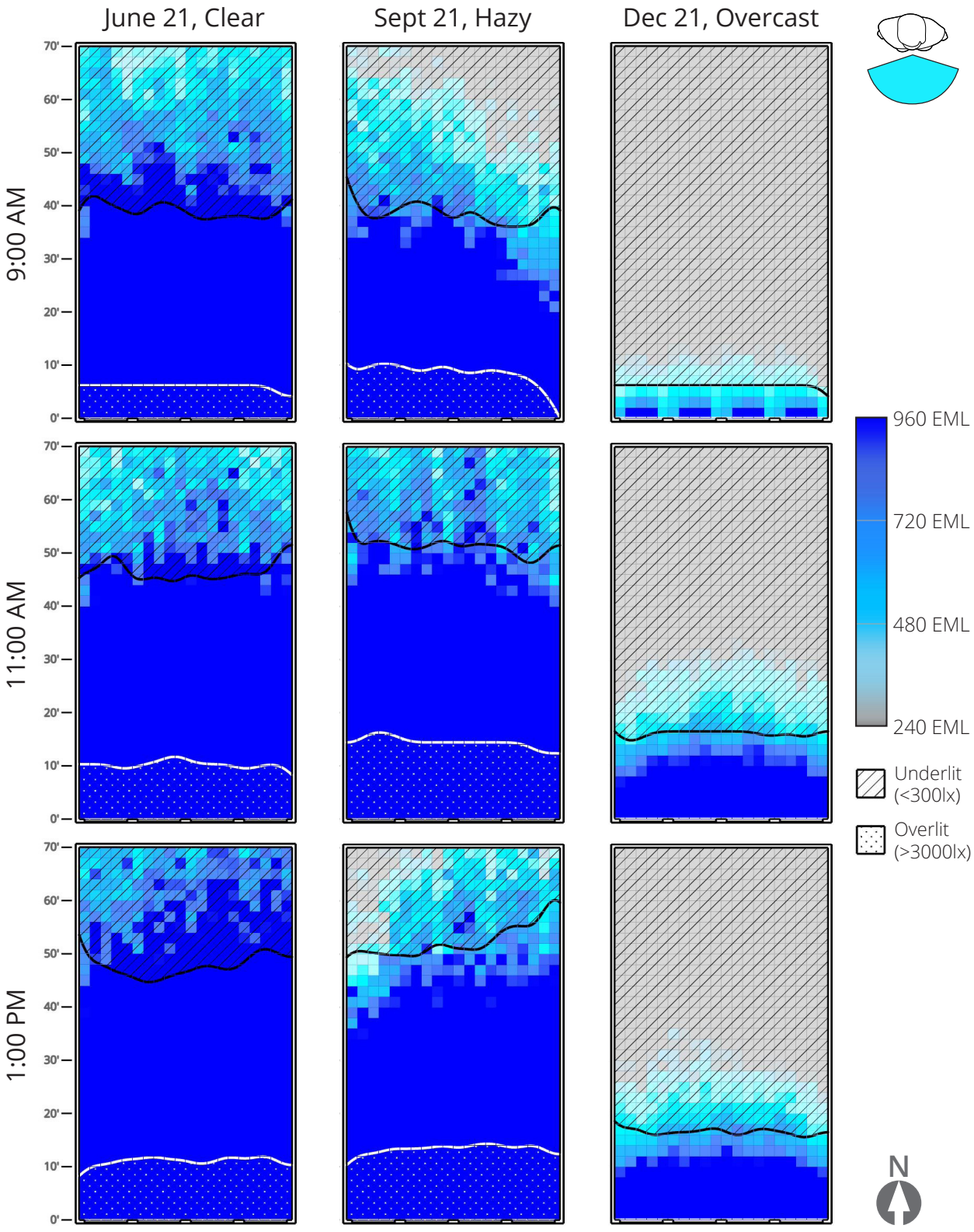




Window Head Height Study - Melanopic Illuminance - Window Front

Building Orientation: South
Window Head Height AFF: 9'-0"
Shading Devices: None

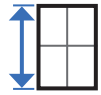
Room Depth: 70'-0"
Site Context: None

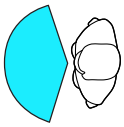


Window Head Height Study - Melanopic Illuminance - Window Right

Building Orientation: South
Window Head Height AFF: 9’-0”
Shading Devices: None

Room Depth: 70’-0”
Site Context: None



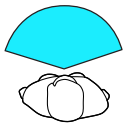


Window Head Height Study - Melanopic Illuminance - Window Behind

Building Orientation: South
Window Head Height AFF: 9'-0"
Shading Devices: None

Room Depth: 70'-0"
Site Context: None



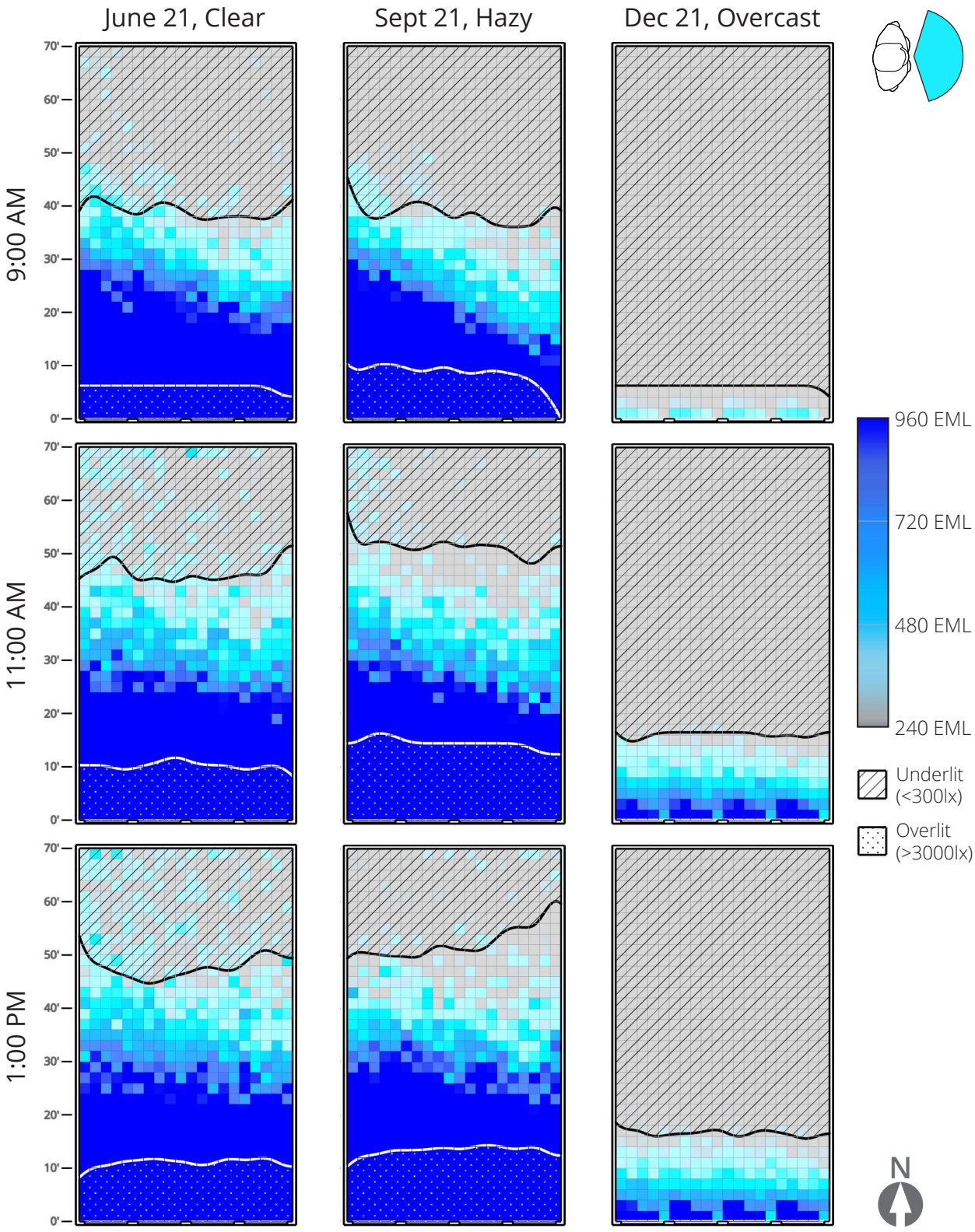


Window Head Height Study - Melanopic Illuminance - Window Left

Building Orientation: South
Window Head Height AFF: 9'-0"
Shading Devices: None

Room Depth: 70'-0"
Site Context: None

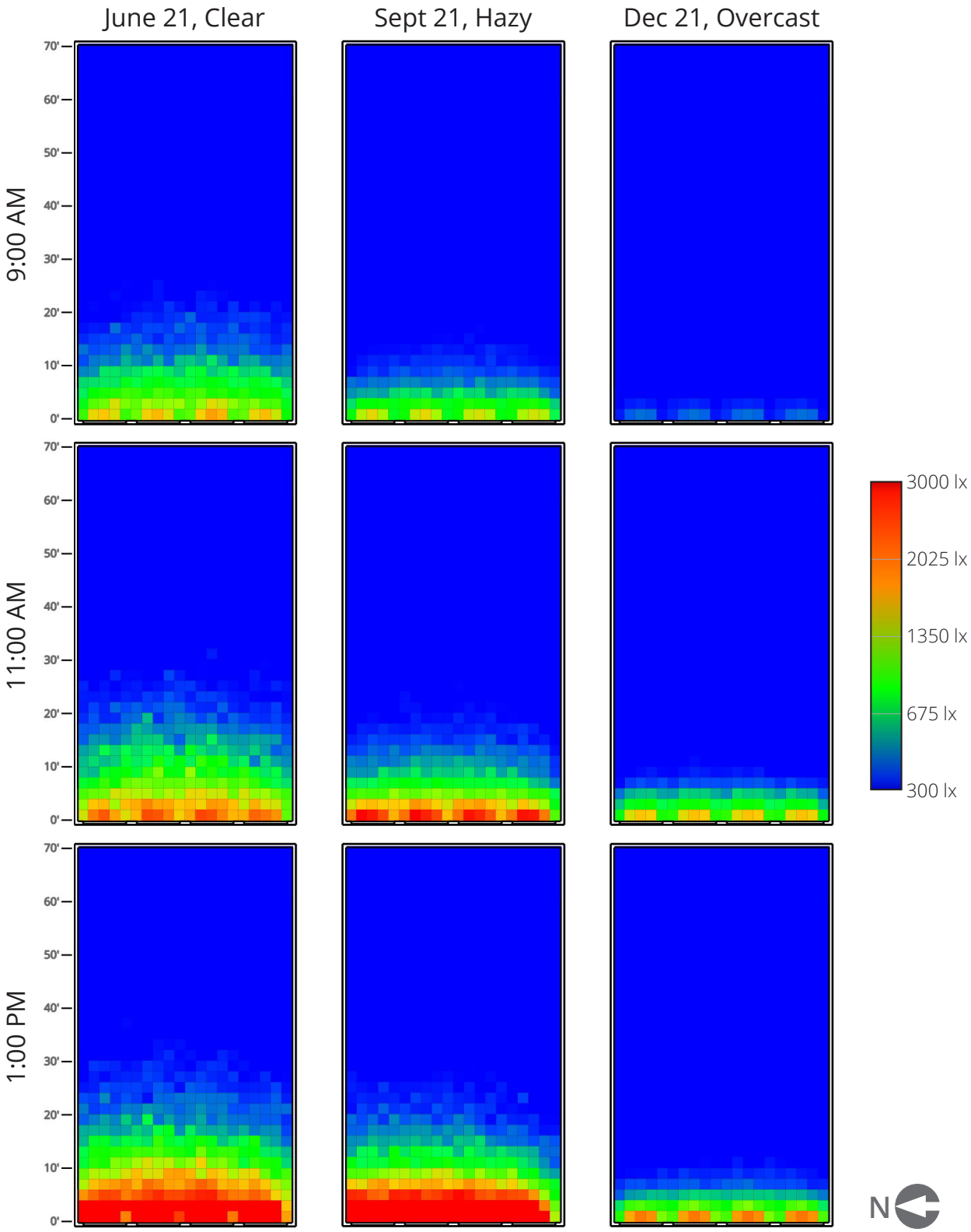




Building Orientation Study - Photopic Illuminance - Workplane Sensors

Building Orientation: West
Window Head Height AFF: 8'-0"
Shading Devices: None

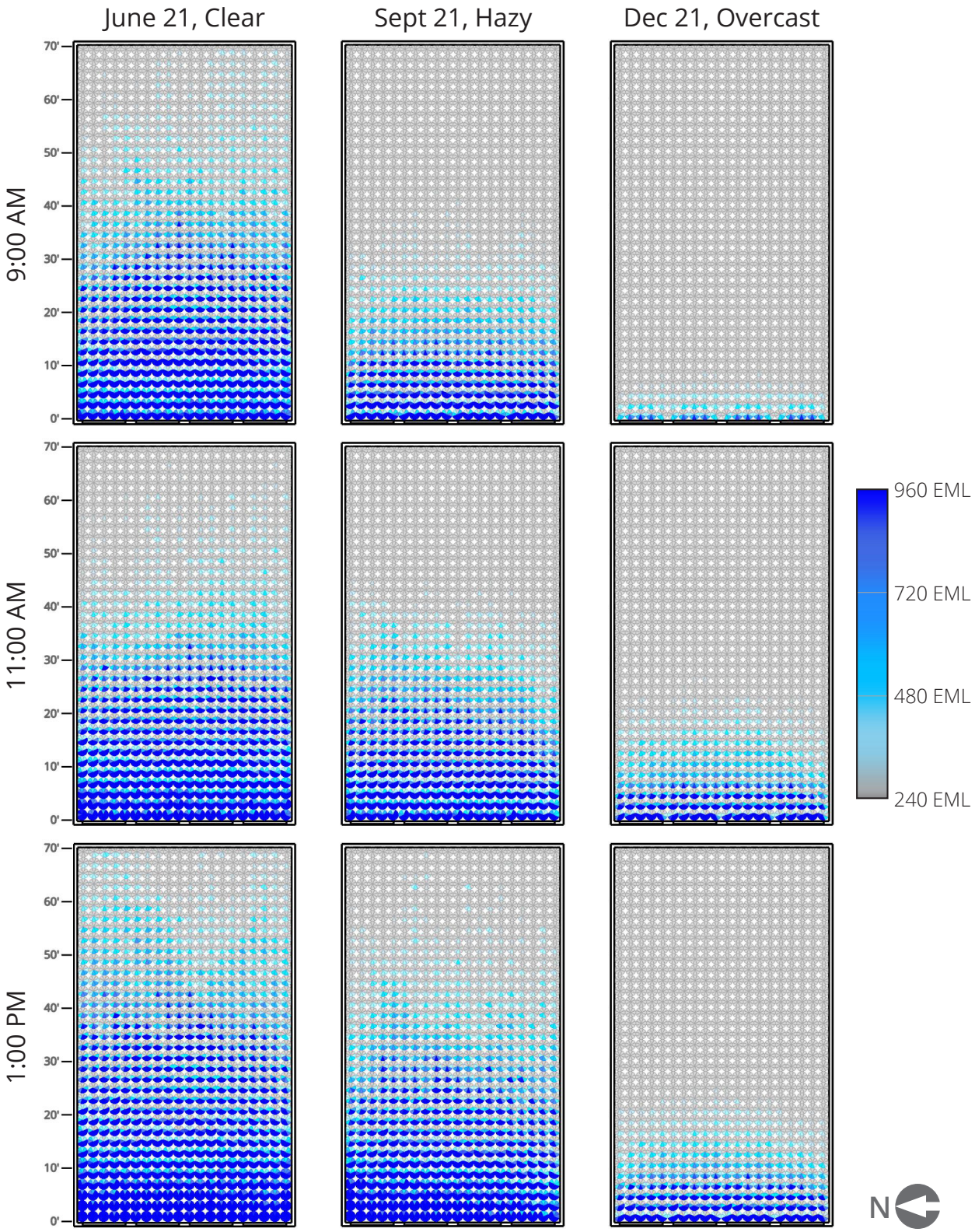
Room Depth: 70'-0"
Site Context: None



Building Orientation Study - Melanopic Illuminance - View Sensors

Building Orientation: West
Window Head Height AFF: 8'-0"
Shading Devices: None

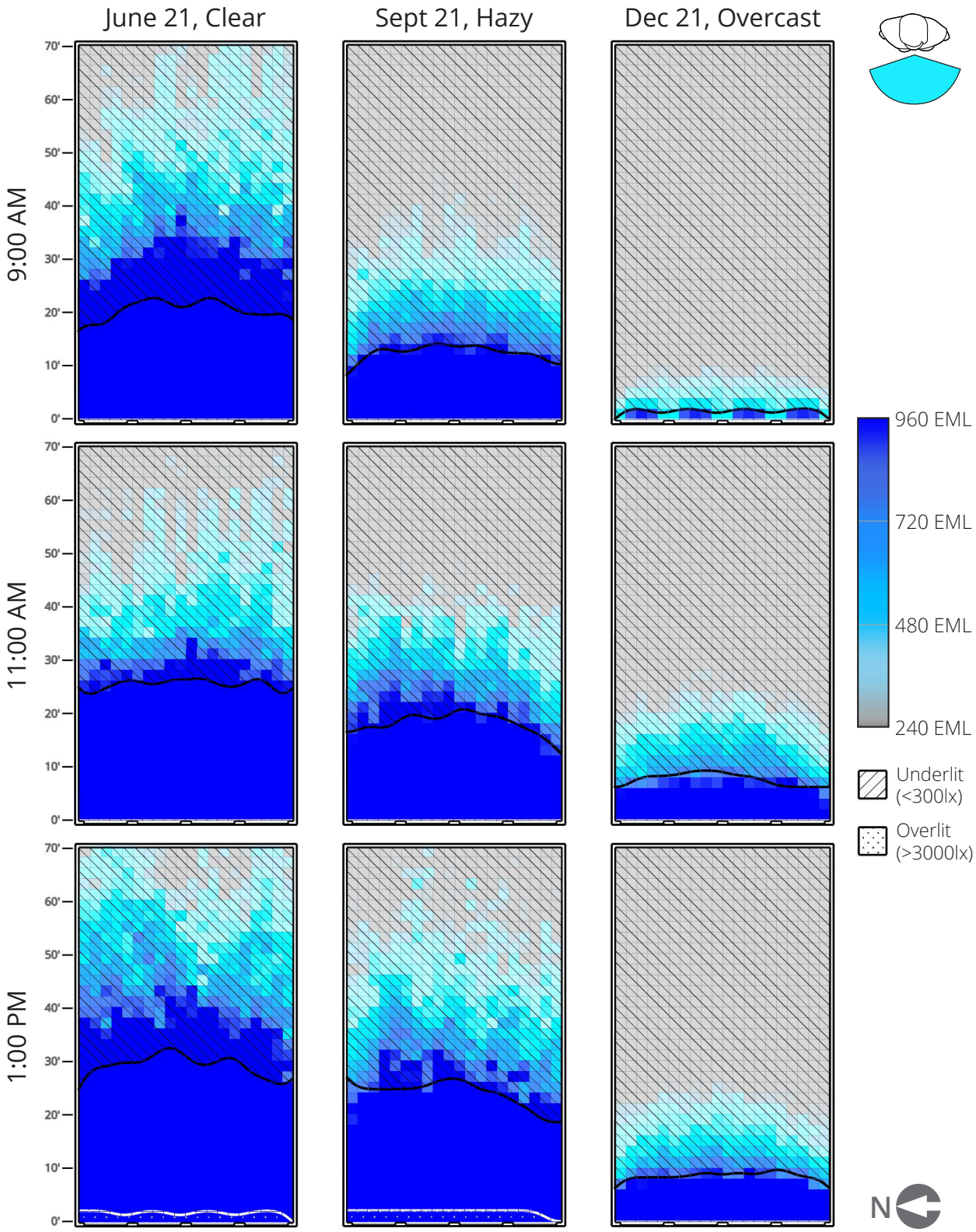
Room Depth: 70'-0"
Site Context: None



Building Orientation - Melanopic Illuminance - Window Front

Building Orientation: West
Window Head Height AFF: 8’-0”
Shading Devices: None

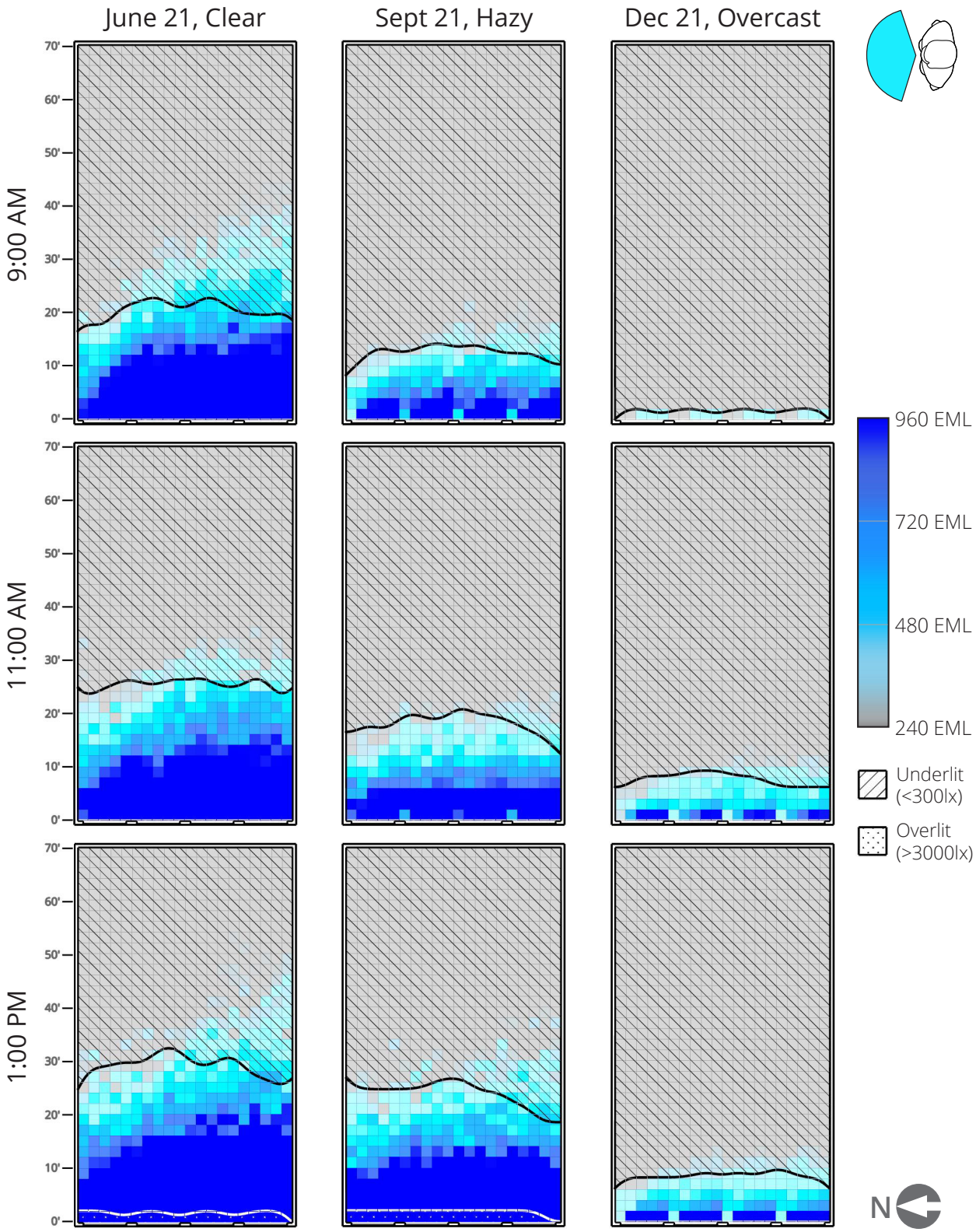
Room Depth: 70’-0”
Site Context: None



Building Orientation Study - Melanopic Illuminance - Window Right

Building Orientation: West
Window Head Height AFF: 8’-0”
Shading Devices: None

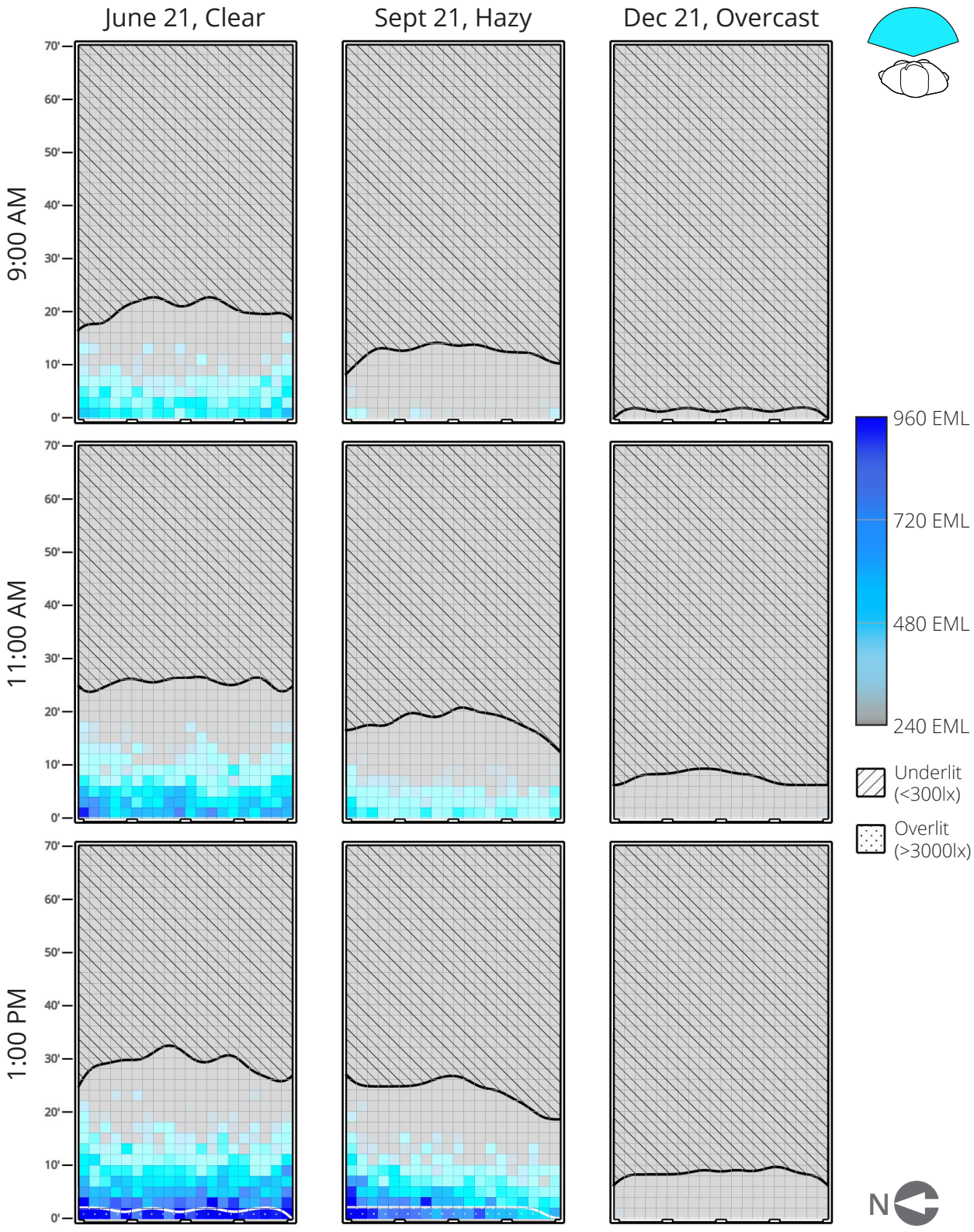
Room Depth: 70’-0”
Site Context: None



Building Orientation Study - Melanopic Illuminance - Window Behind

Building Orientation: West
Window Head Height AFF: 8’-0”
Shading Devices: None

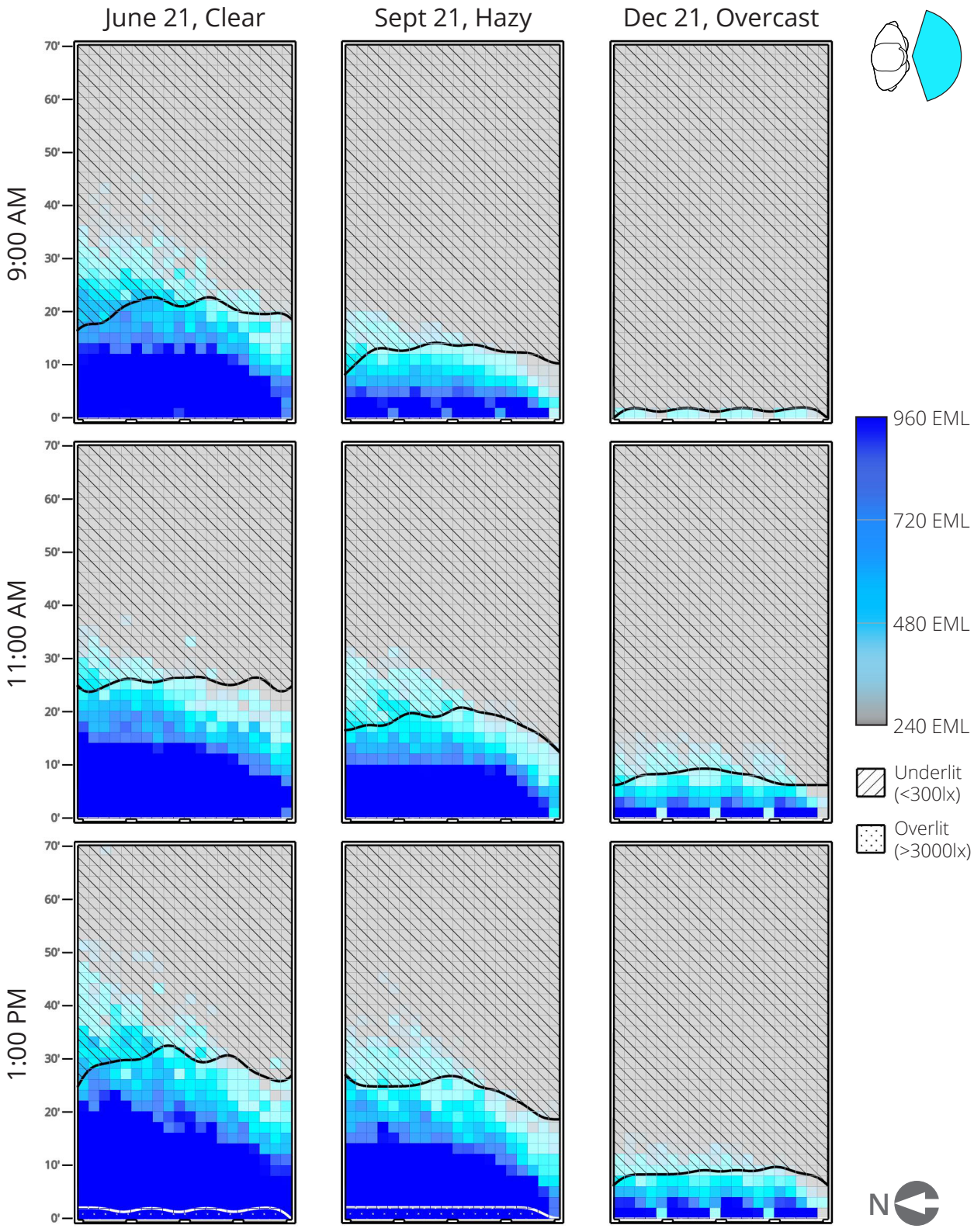
Room Depth: 70’-0”
Site Context: None



Building Orientation Study - Melanopic Illuminance - Window Left

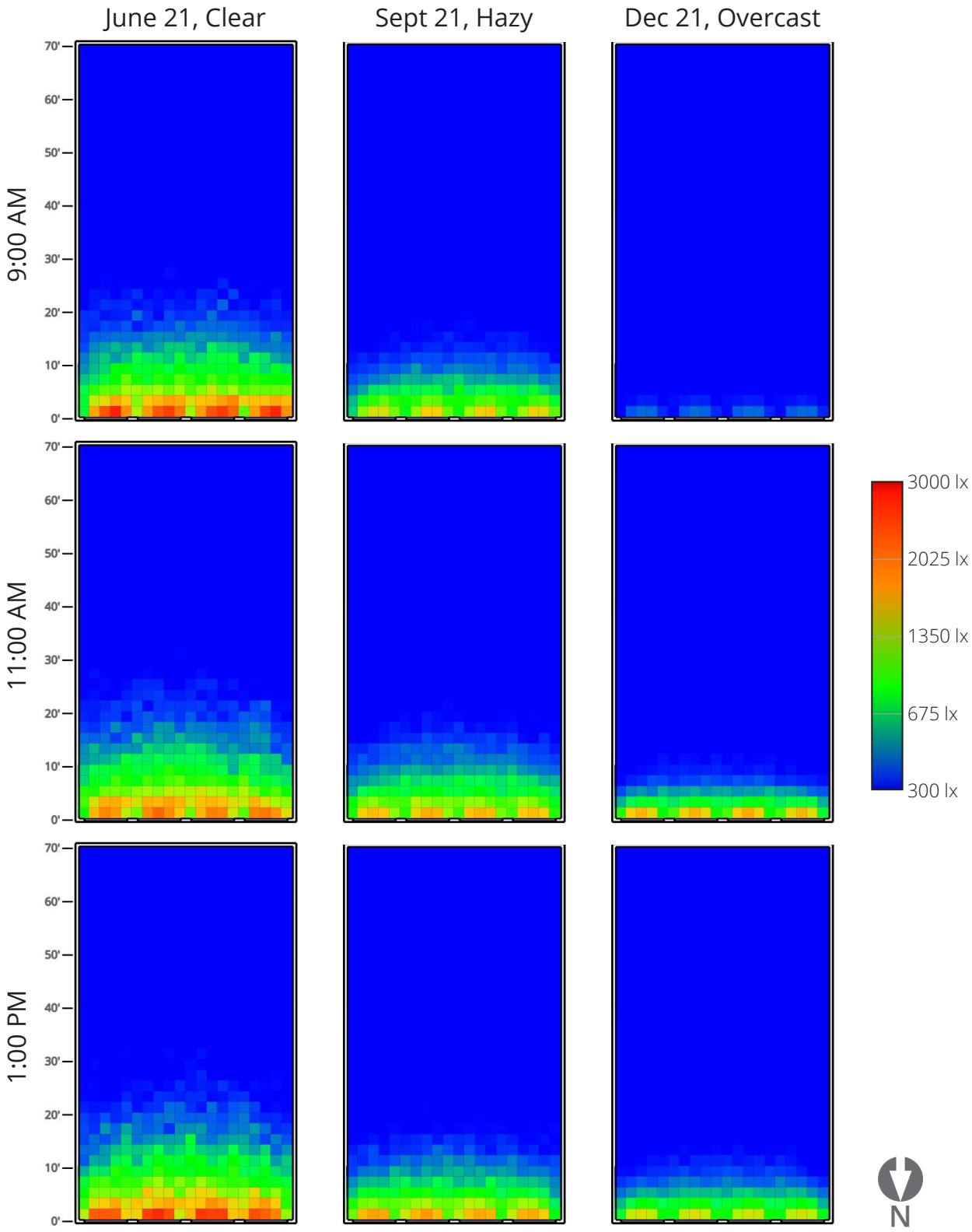
Building Orientation: West
Window Head Height AFF: 8'-0"
Shading Devices: None

Room Depth: 70'-0"
Site Context: None



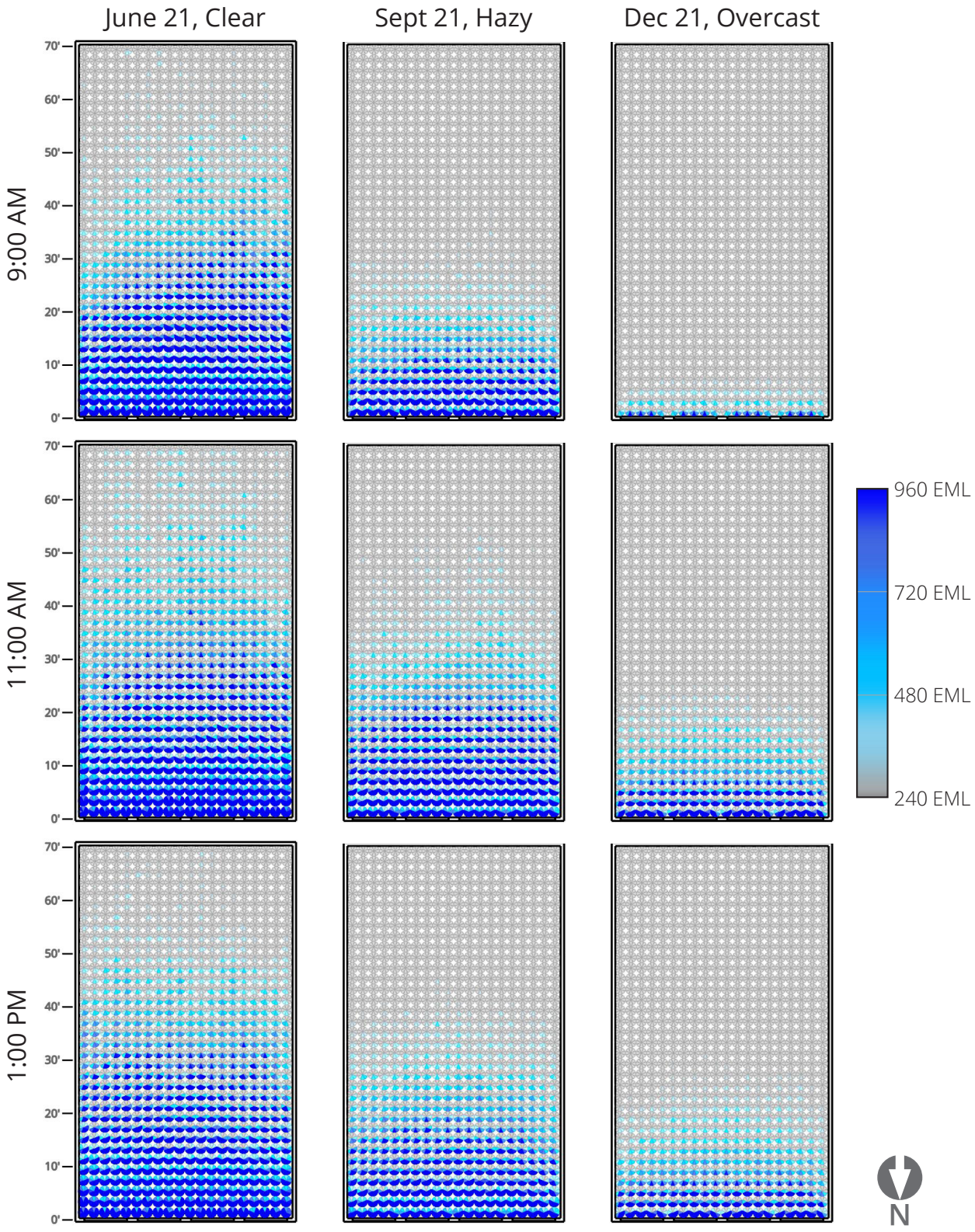
Building Orientation Study - Photopic Illuminance - Workplane Sensors

Building Orientation: North
Window Head Height AFF: 8'-0"
Shading Devices: None
Room Depth: 70'-0"
Site Context: None



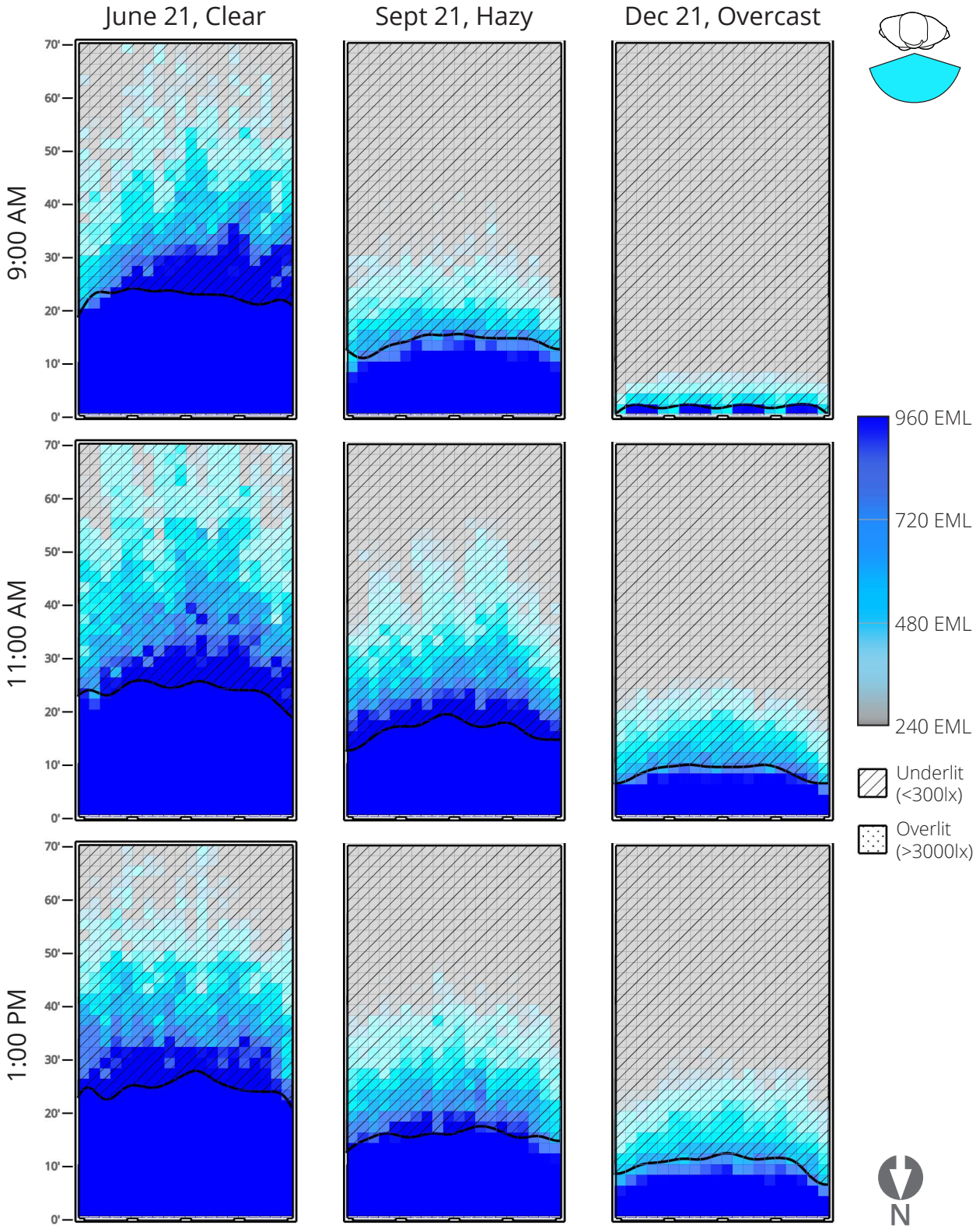
Building Orientation Study - Melanopic Illuminance - View Sensors

Building Orientation: North
Window Head Height AFF: 8'-0"
Shading Devices: None
Room Depth: 70'-0"
Site Context: None



Building Orientation - Melanopic Illuminance - Window Front

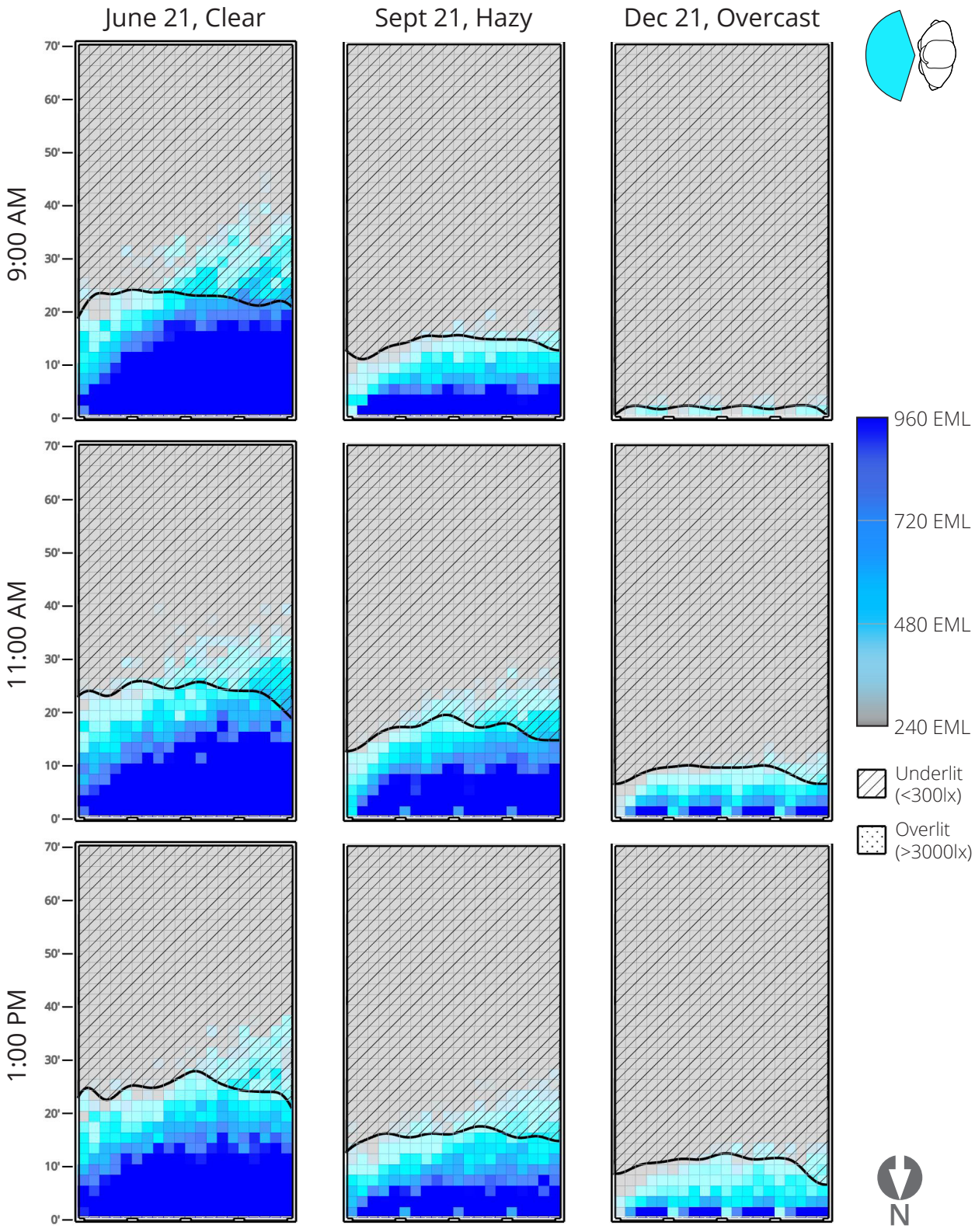
Building Orientation: North
Window Head Height AFF: 8'-0"
Shading Devices: None
Room Depth: 70'-0"
Site Context: None



Building Orientation Study - Melanopic Illuminance - Window Right

Building Orientation: North
Window Head Height AFF: 8'-0"
Shading Devices: None

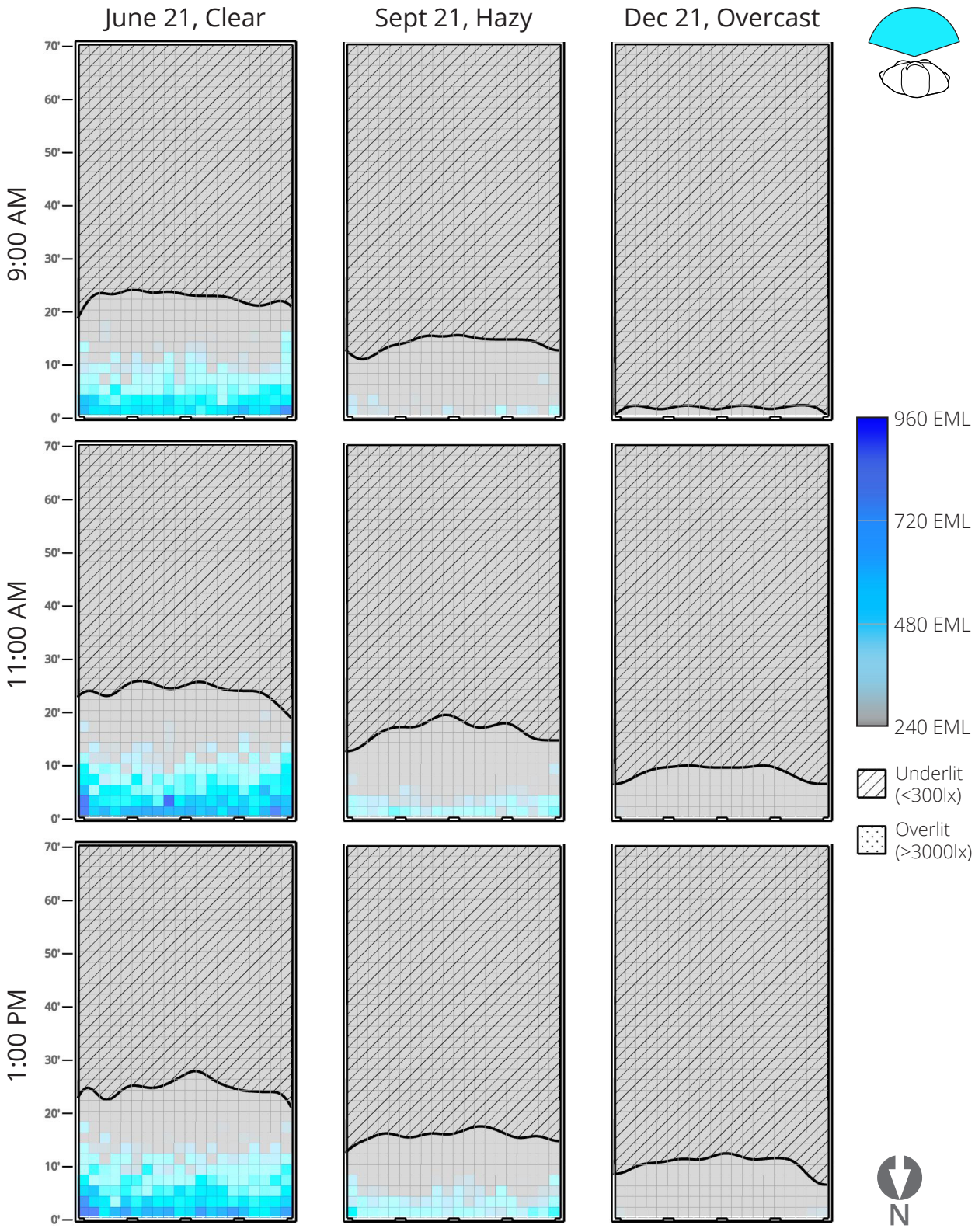
Room Depth: 70'-0"
Site Context: None



Building Orientation Study - Melanopic Illuminance - Window Behind

Building Orientation: North
Window Head Height AFF: 8’-0”
Shading Devices: None

Room Depth: 70’-0”
Site Context: None

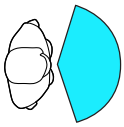


Building Orientation Study - Melanopic Illuminance - Window Left

Building Orientation: North
Window Head Height AFF: 8'-0"
Shading Devices: None

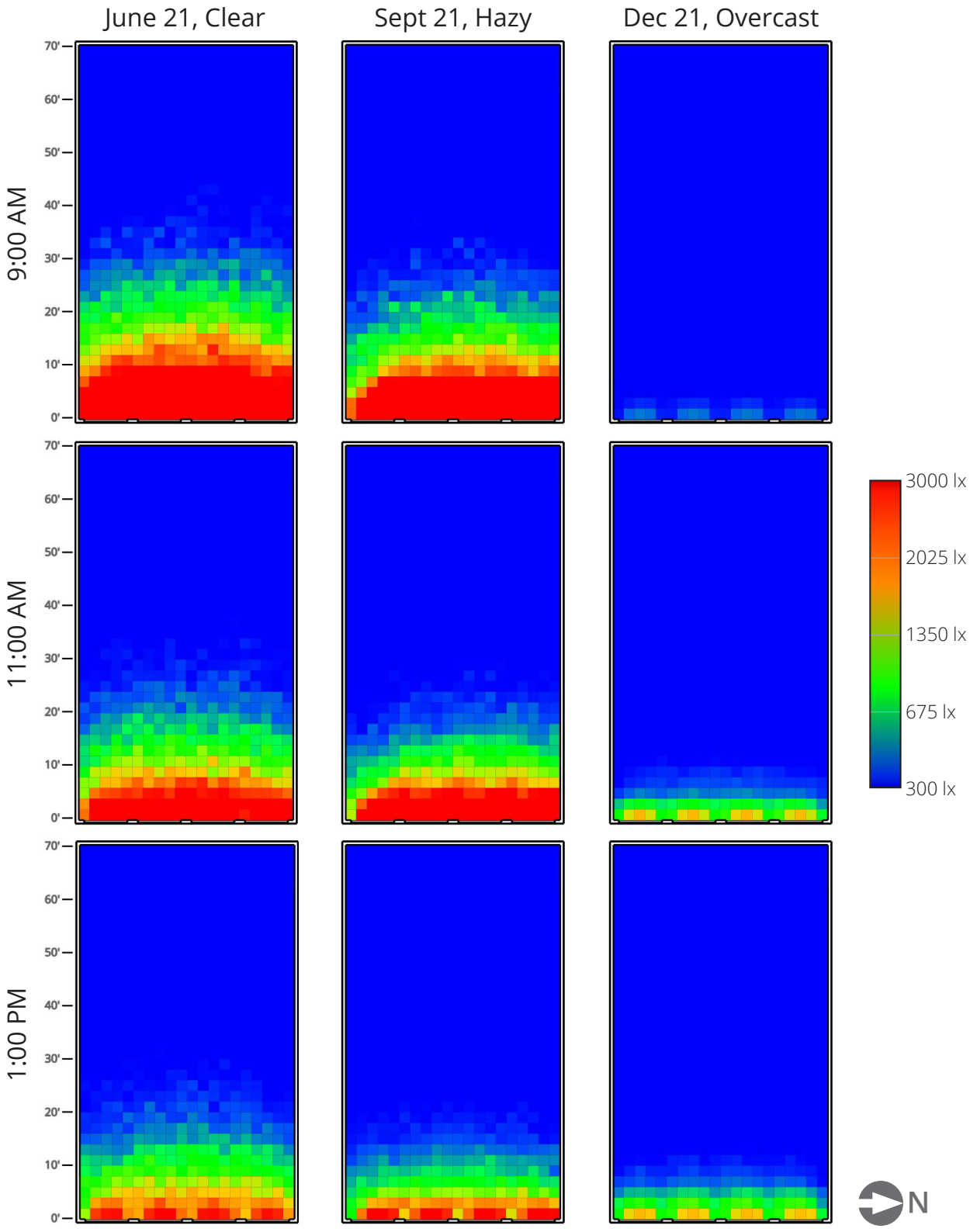
Room Depth: 70'-0"
Site Context: None





Building Orientation Study - Photopic Illuminance - Workplane Sensors

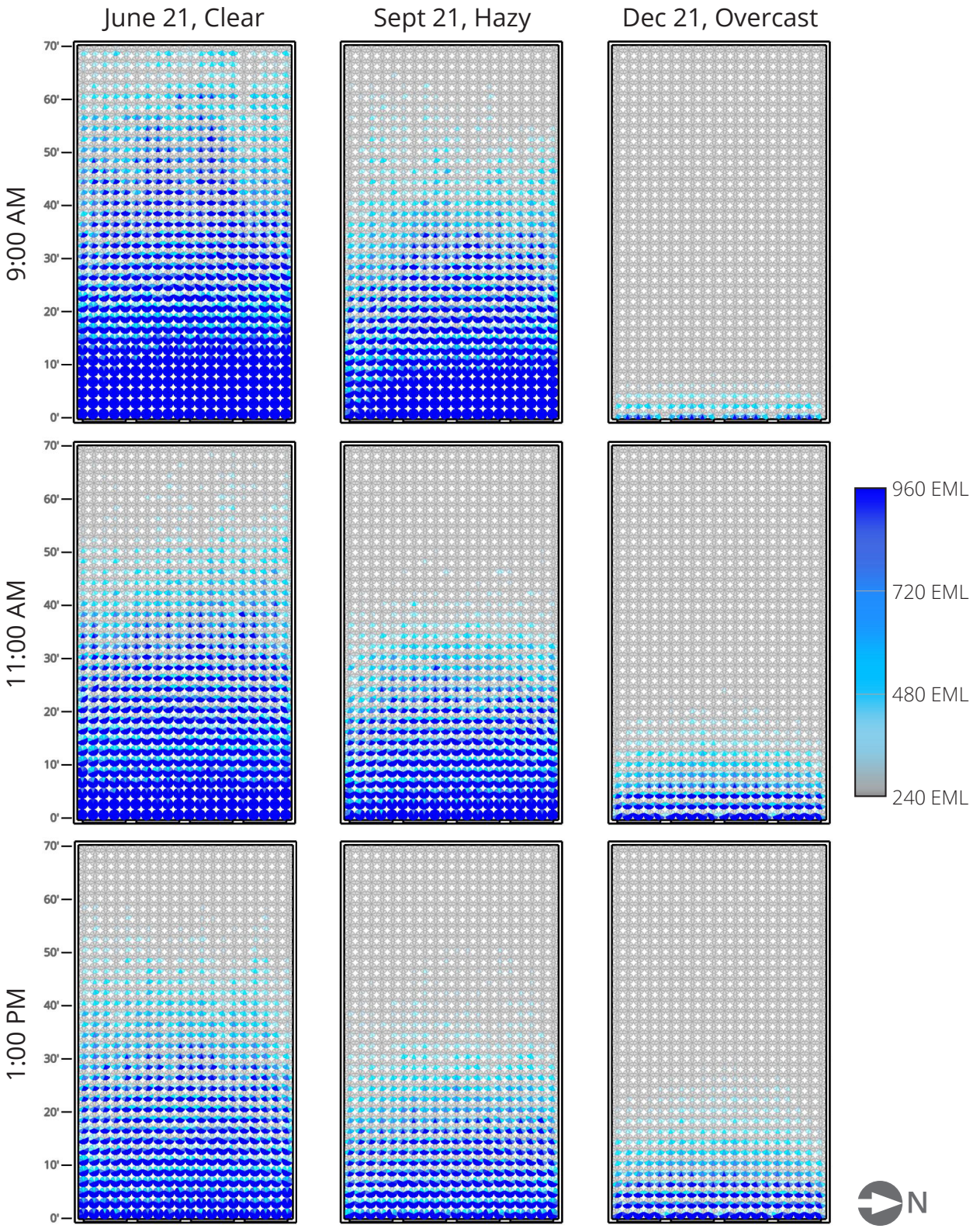
Building Orientation: East
Window Head Height AFF: 8'-0"
Shading Devices: None
Room Depth: 70'-0"
Site Context: None



Building Orientation Study - Melanopic Illuminance - View Sensors

Building Orientation: East
Window Head Height AFF: 8'-0"
Shading Devices: None

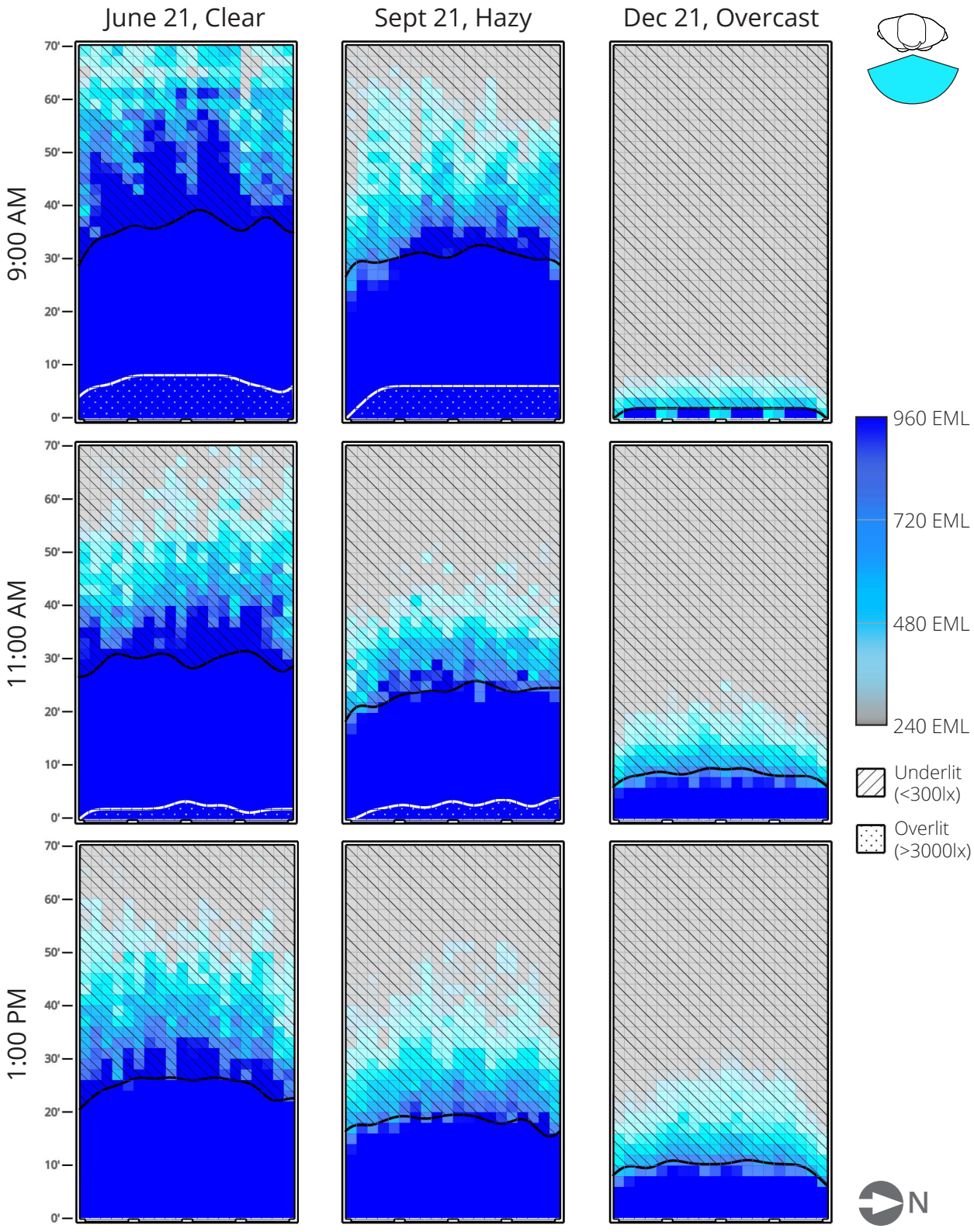
Room Depth: 70'-0"
Site Context: None



Building Orientation - Melanopic Illuminance - Window Front

Building Orientation: East
Window Head Height AFF: 8’-0”
Shading Devices: None

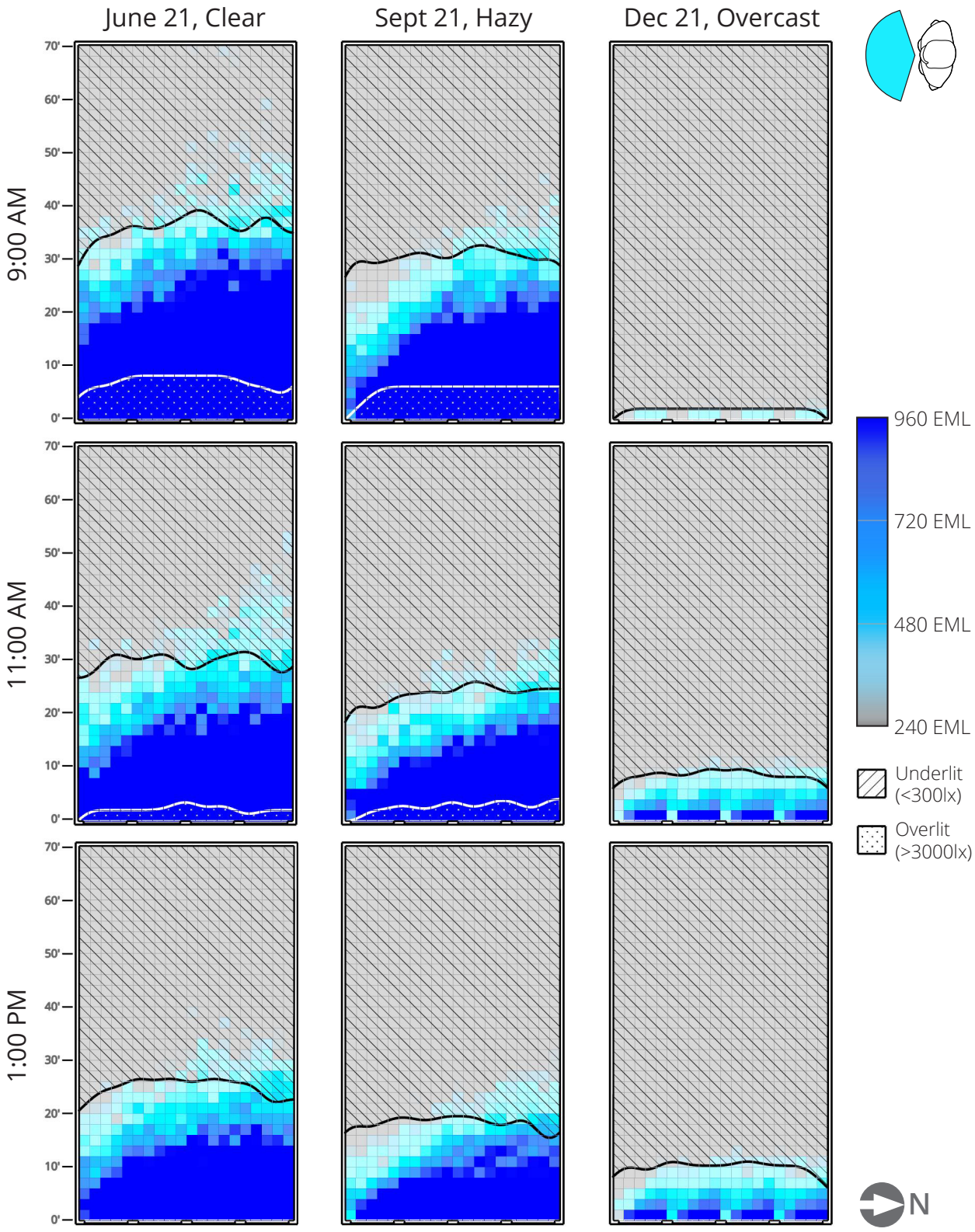
Room Depth: 70’-0”
Site Context: None



Building Orientation Study - Melanopic Illuminance - Window Right

Building Orientation: East
Window Head Height AFF: 8'-0"
Shading Devices: None

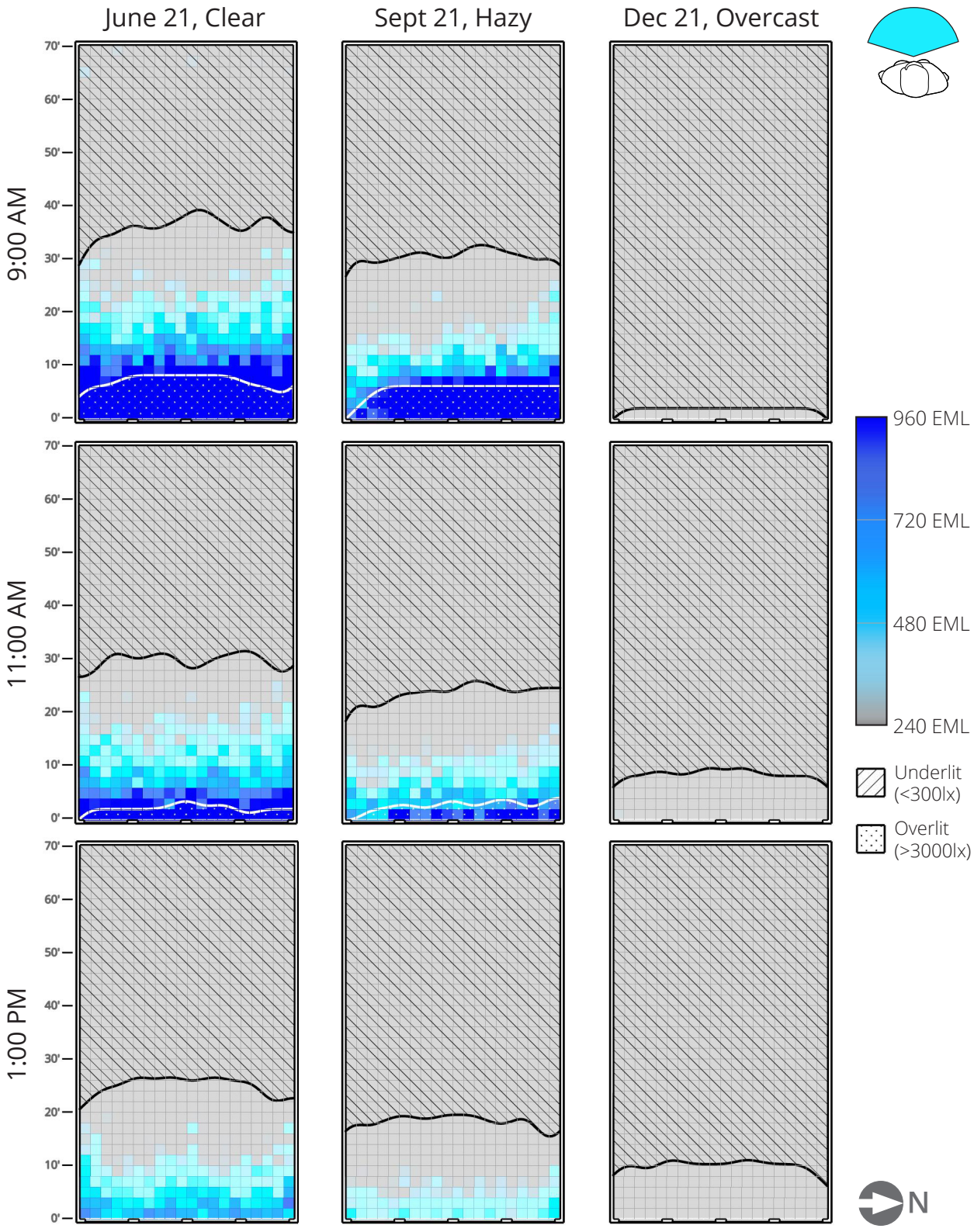
Room Depth: 70'-0"
Site Context: None



Building Orientation Study - Melanopic Illuminance - Window Behind

Building Orientation: East
Window Head Height AFF: 8’-0”
Shading Devices: None

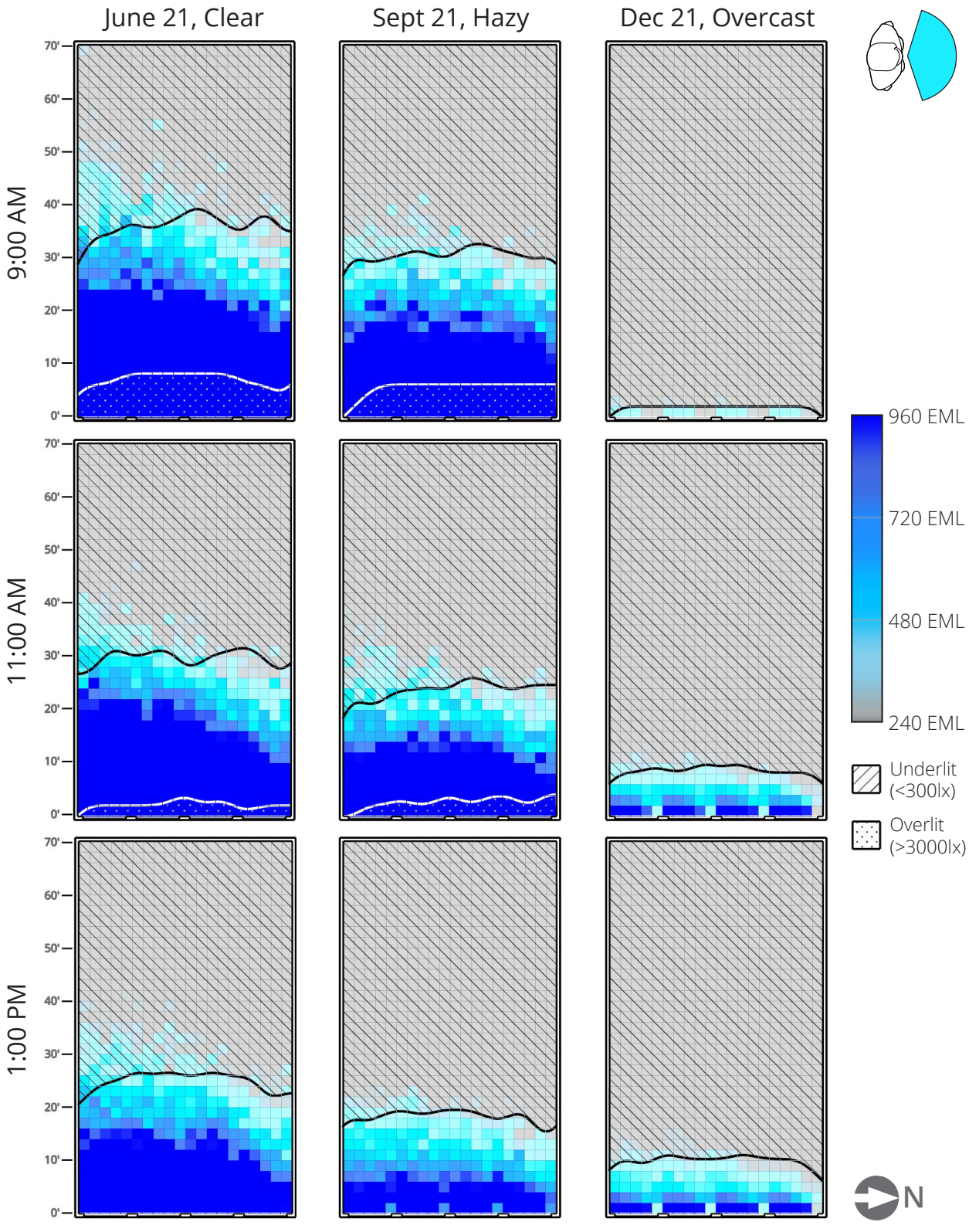
Room Depth: 70’-0”
Site Context: None



Building Orientation Study - Melanopic Illuminance - Window Left

Building Orientation: East
Window Head Height AFF: 8'-0"
Shading Devices: None

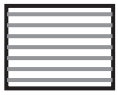
Room Depth: 70'-0"
Site Context: None

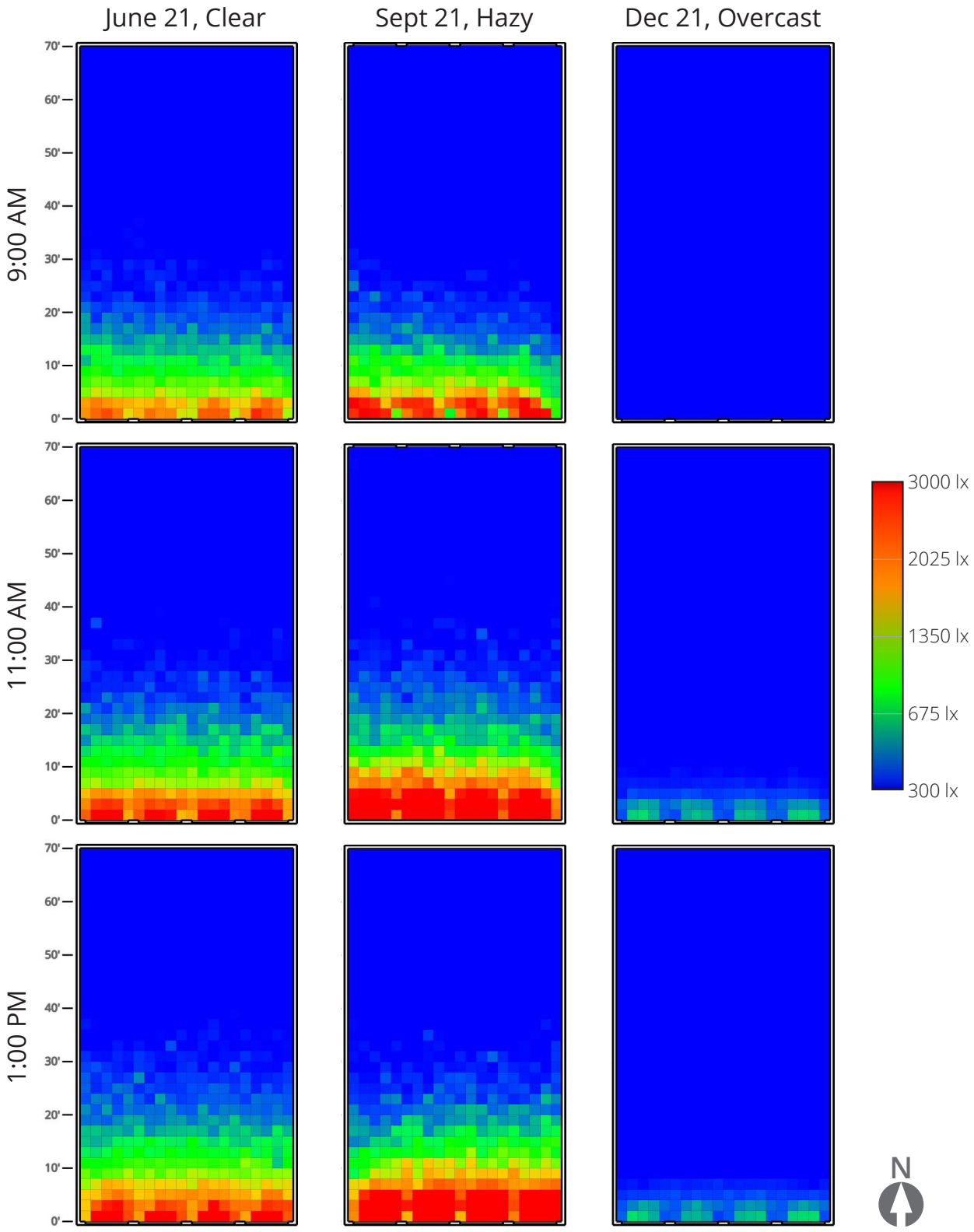


Shading Devices Study - Photopic Illuminance - Workplane Sensors

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Awning (Mar 21st - Sept 21st)

Room Depth: 70'-0"
Site Context: None

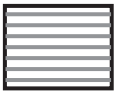


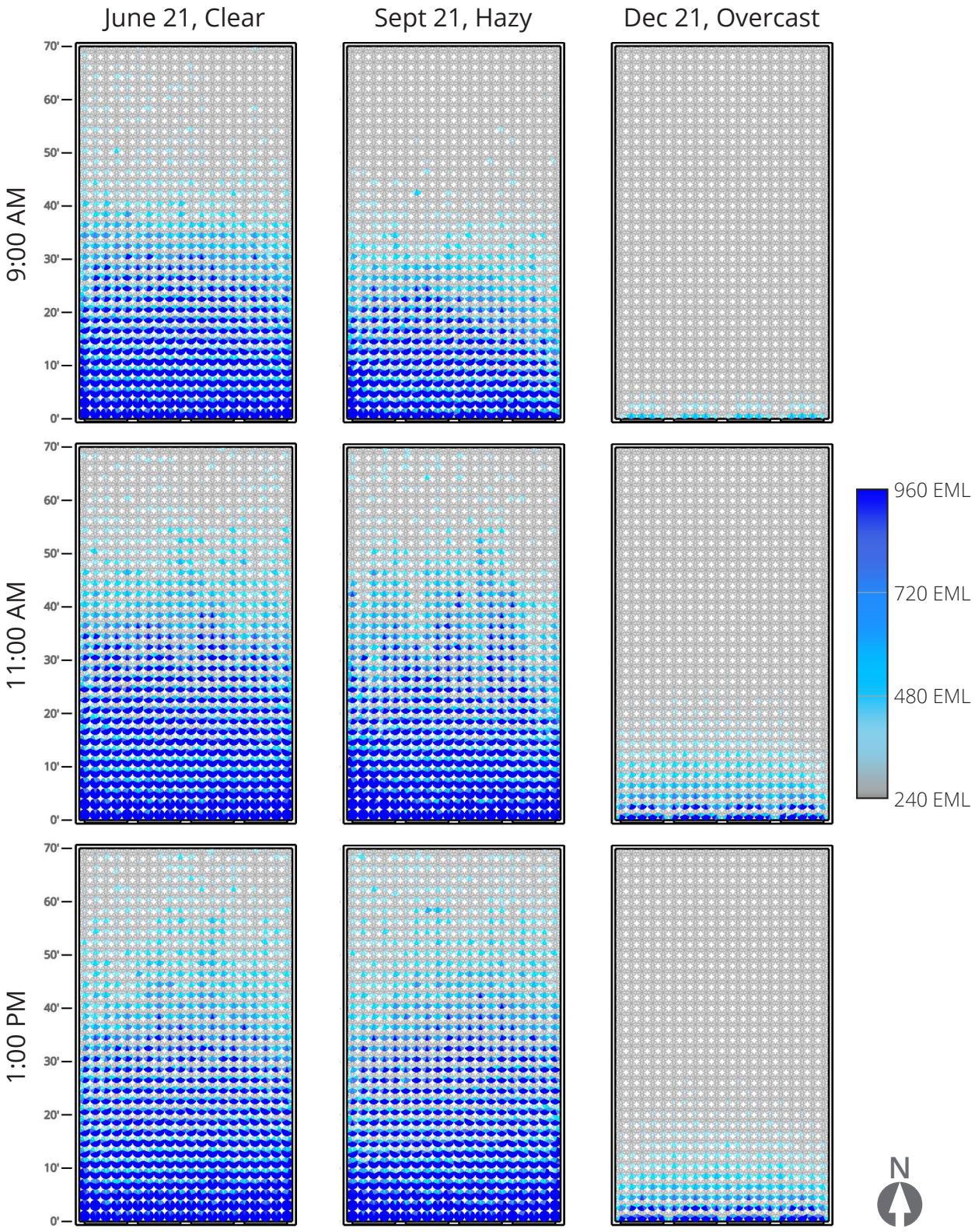


Shading Devices Study - Melanopic Illuminance - View Sensors

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Awning (Mar 21st - Sept 21st)

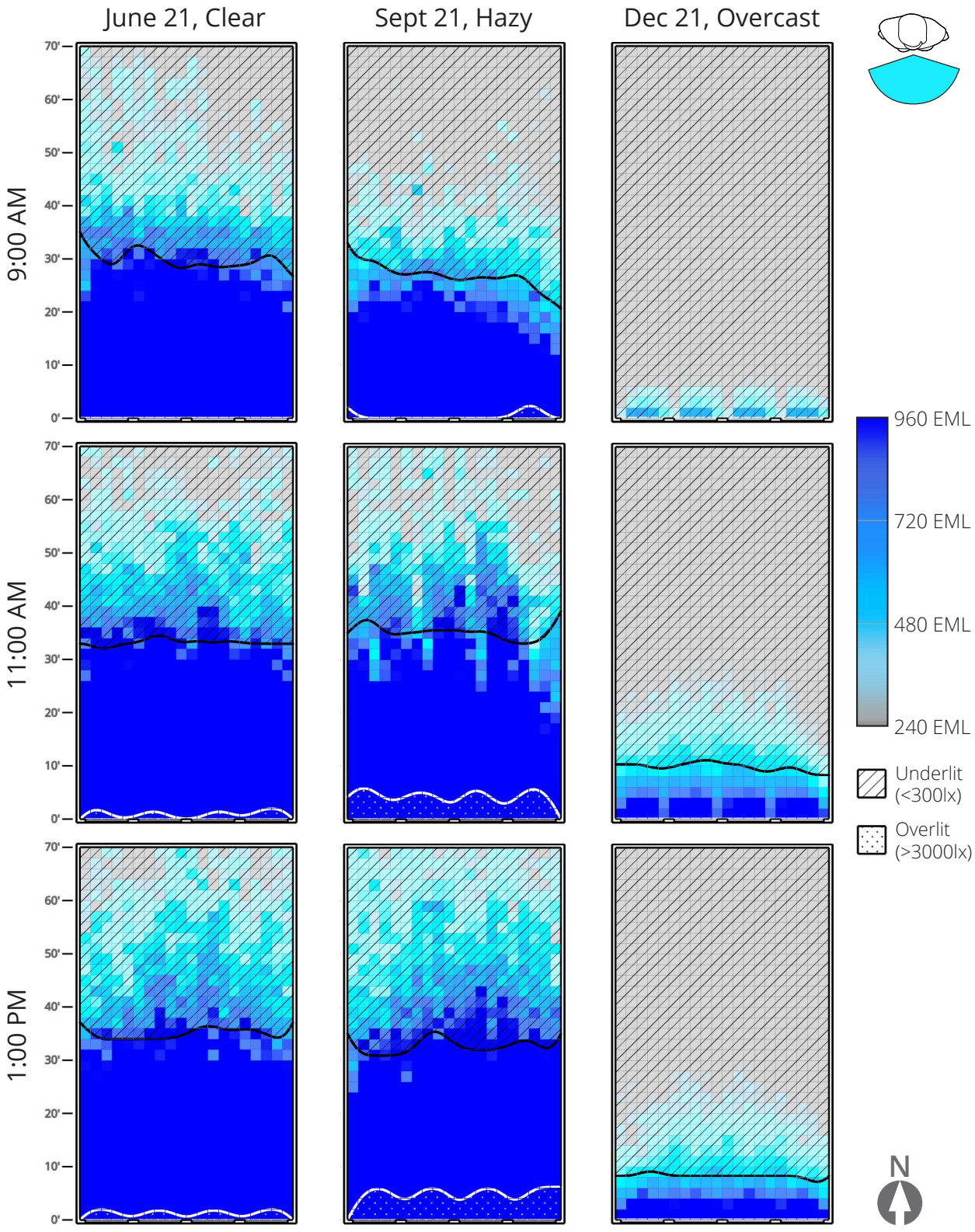
Room Depth: 70'-0"
Site Context: None





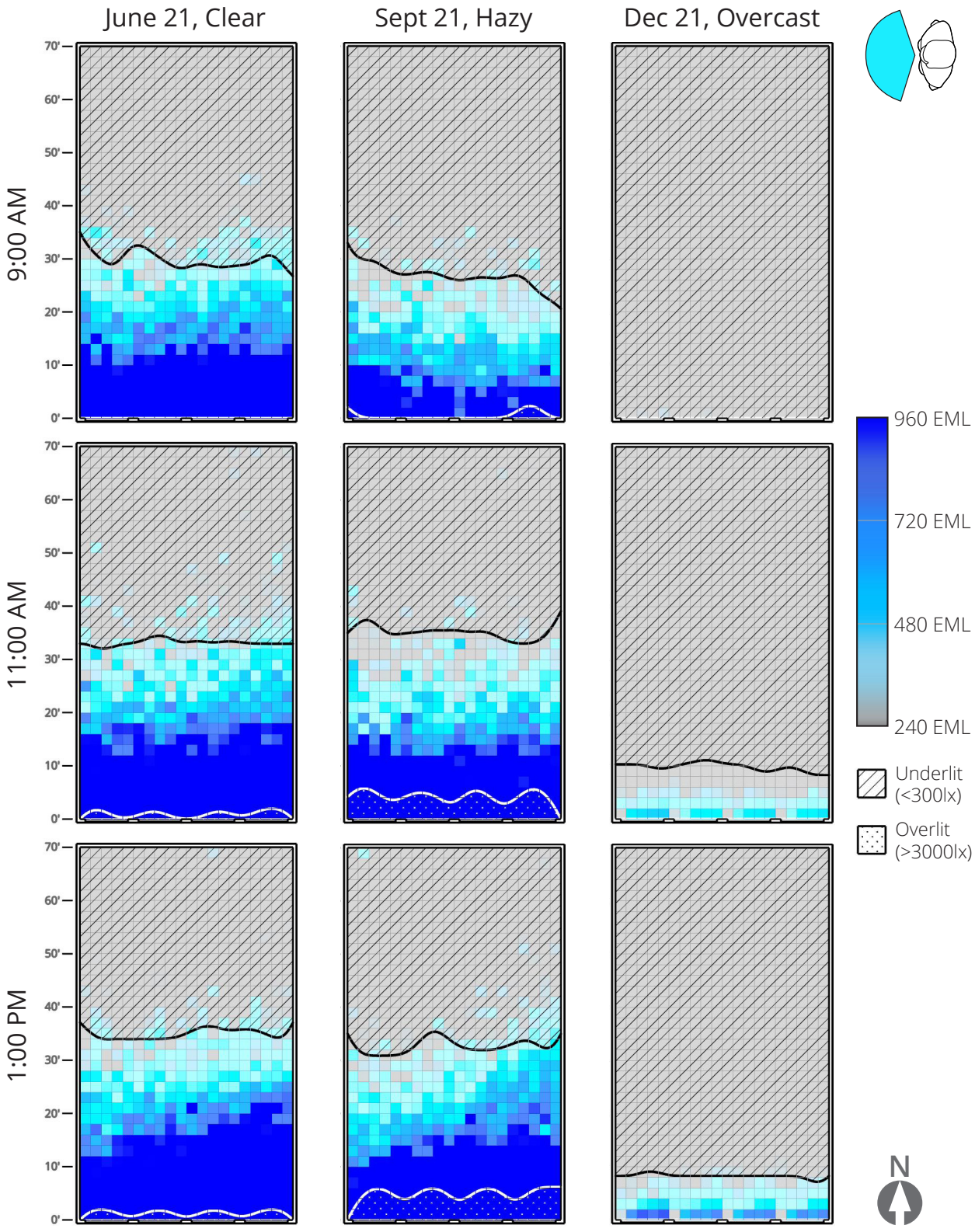
Shading Devices Study - Melanopic Illuminance - Window Front

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Awning (Mar 21st - Sept 21st)
Room Depth: 70'-0"
Site Context: None



Shading Devices Study - Melanopic Illuminance - Window Right

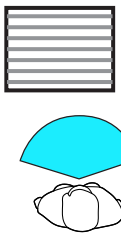
Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Awning (Mar 21st - Sept 21st)
Room Depth: 70'-0"
Site Context: None



Shading Devices Study - Melanopic Illuminance - Window Behind

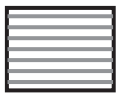
Building Orientation: South
Window Head Height AFF: 8’-0”
Shading Devices: Awning (Mar 21st - Sept 21st)

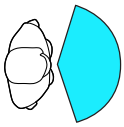
Room Depth: 70’-0”
Site Context: None



Shading Devices Study - Melanopic Illuminance - Window Left

Building Orientation: South
Window Head Height AFF: 8’-0”
Shading Devices: Awning (Mar 21st - Sept 21st)
Room Depth: 70’-0”
Site Context: None

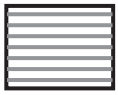


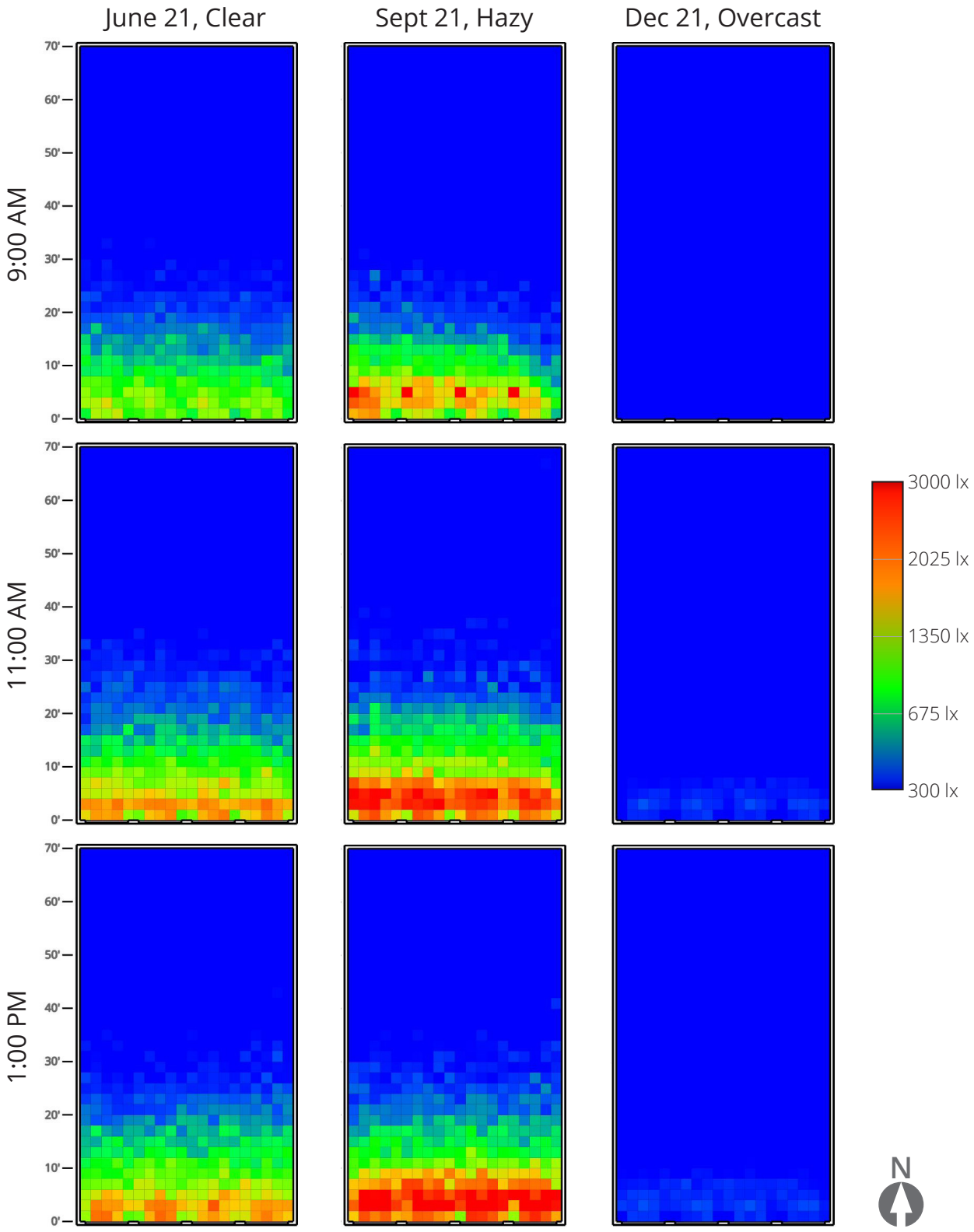


Shading Devices Study - Photopic Illuminance - Workplane Sensors

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Blinds (Mar 21st - Sept 21st)

Room Depth: 70'-0"
Site Context: None

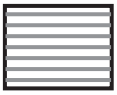


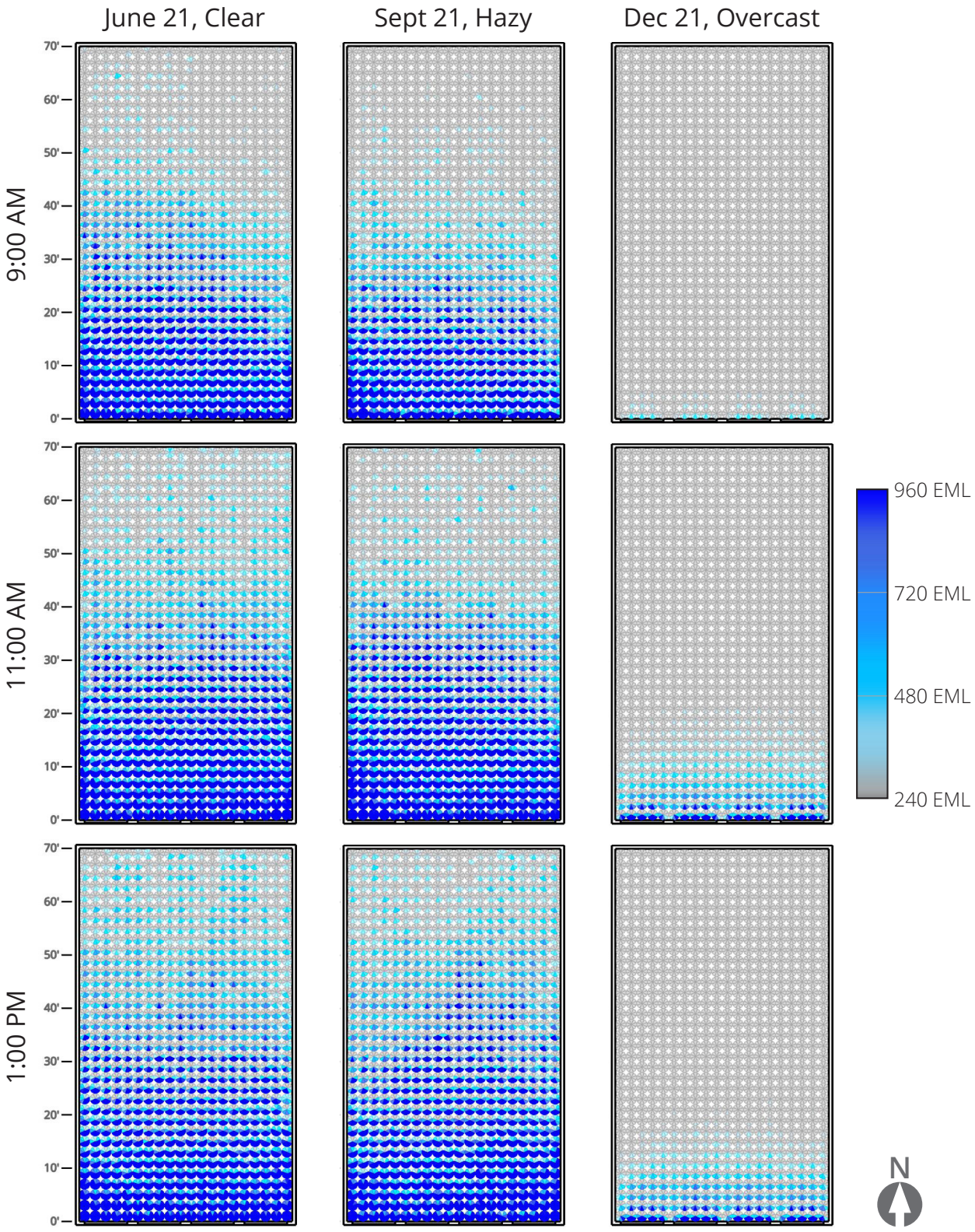


Shading Devices Study - Melanopic Illuminance - View Sensors

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Blinds (Mar 21st - Sept 21st)

Room Depth: 70'-0"
Site Context: None

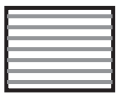


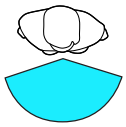


Shading Devices Study - Melanopic Illuminance - Window Front

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Blinds (Mar 21st - Sept 21st)

Room Depth: 70'-0"
Site Context: None

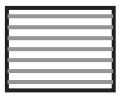


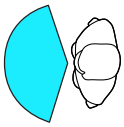


Shading Devices Study - Melanopic Illuminance - Window Right

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Blinds (Mar 21st - Sept 21st)

Room Depth: 70'-0"
Site Context: None

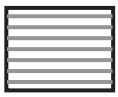


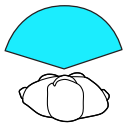


Shading Devices Study - Melanopic Illuminance - Window Behind

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Blinds (Mar 21st - Sept 21st)

Room Depth: 70'-0"
Site Context: None

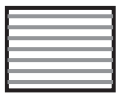


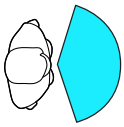


Shading Devices Study - Melanopic Illuminance - Window Left

Building Orientation: South
Window Head Height AFF: 8’-0”
Shading Devices: Blinds (Mar 21st - Sept 21st)

Room Depth: 70’-0”
Site Context: None

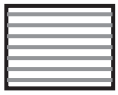


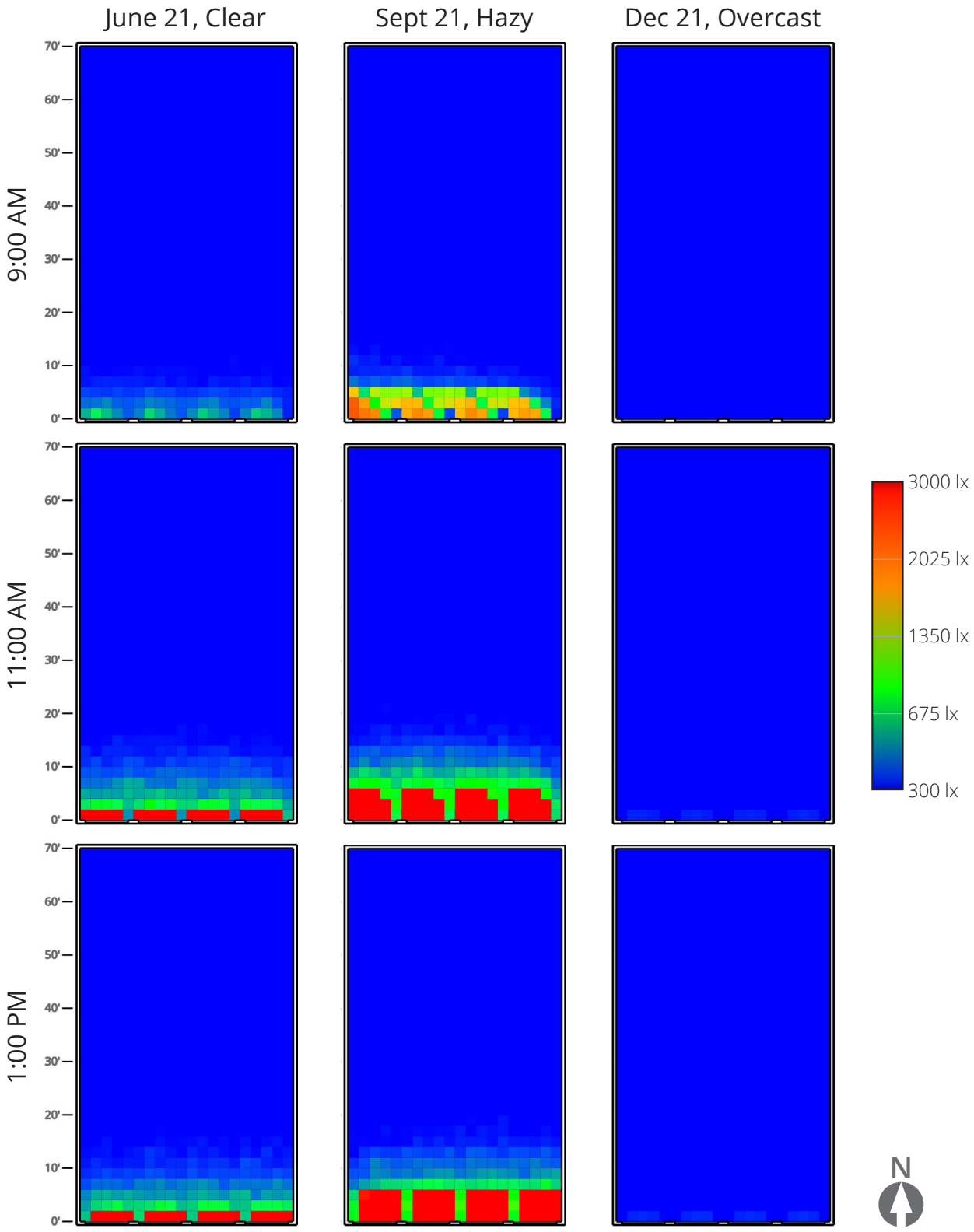


Shading Devices Study - Photopic Illuminance - Workplane Sensors

Building Orientation: South
Window Head Height AFF: 8’-0”
Shading Devices: Electrochromic 18%

Room Depth: 70’-0”
Site Context: None

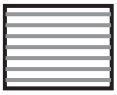


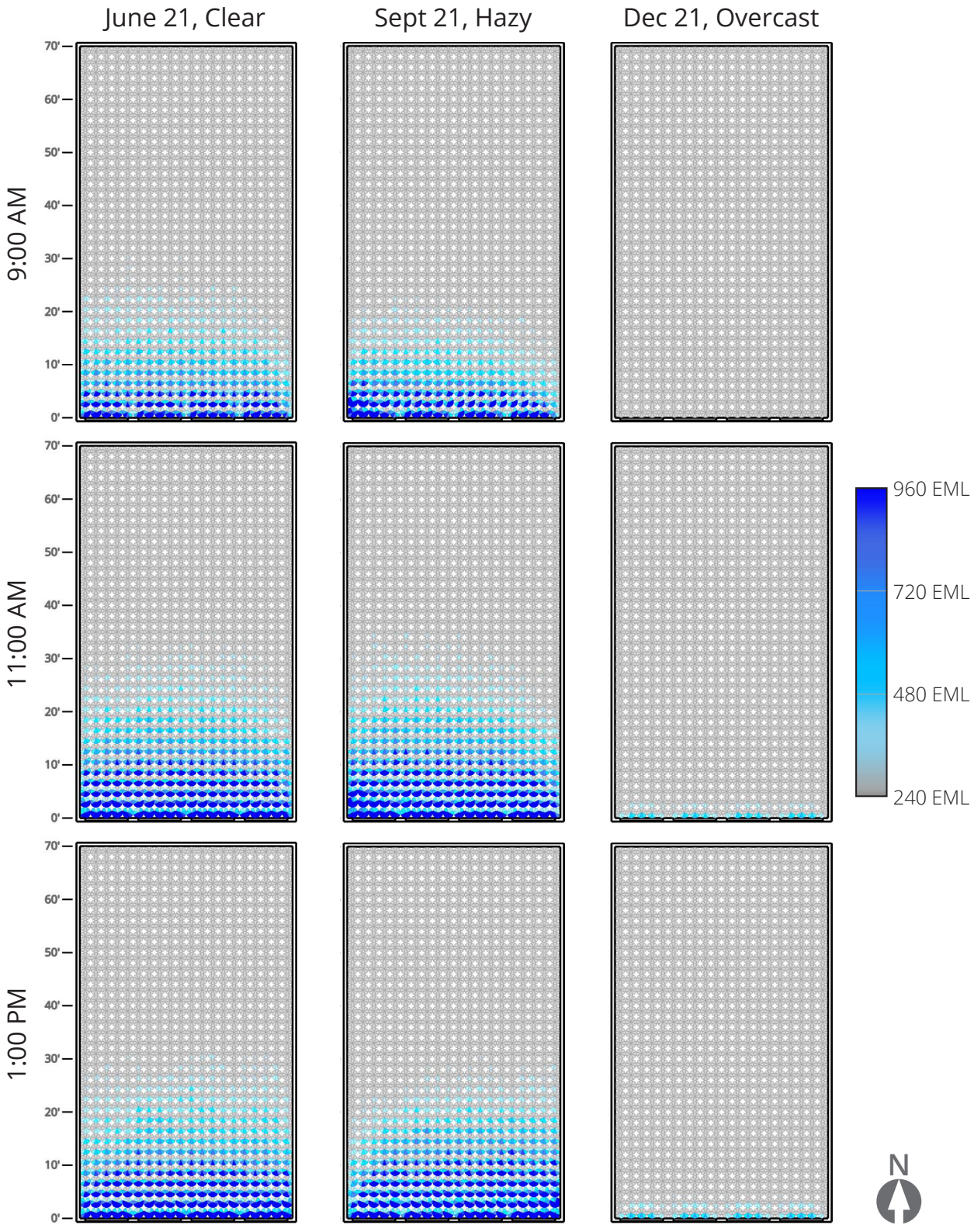


Shading Devices Study - Melanopic Illuminance - View Sensors

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Electrochromic 18%

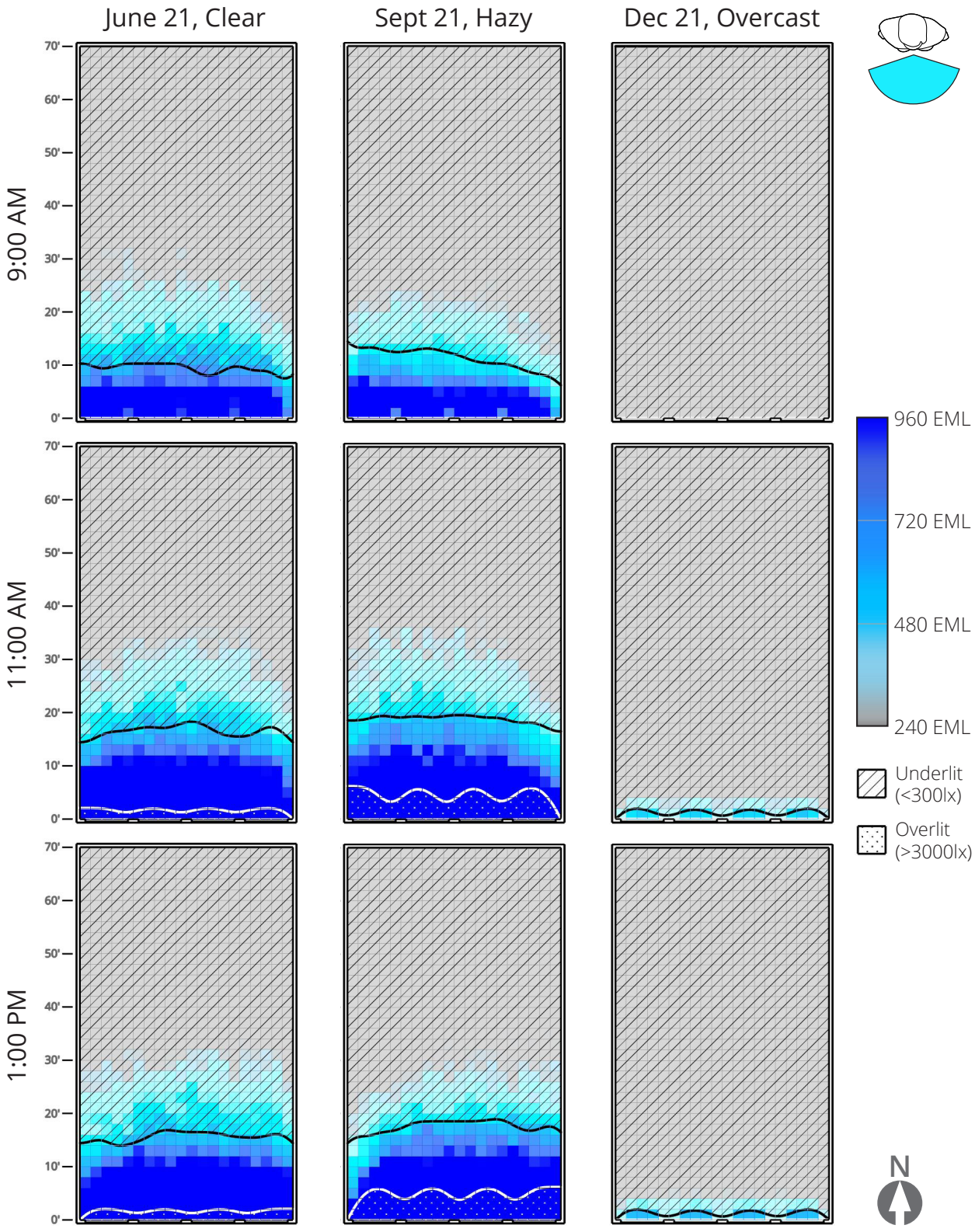
Room Depth: 70'-0"
Site Context: None





Shading Devices Study - Melanopic Illuminance - Window Front

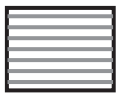
Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Electrochromic 18%
Room Depth: 70'-0"
Site Context: None

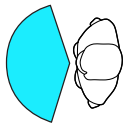


Shading Devices Study - Melanopic Illuminance - Window Right

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Electrochromic 18%

Room Depth: 70'-0"
Site Context: None

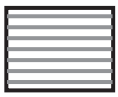


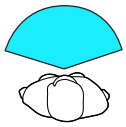


Shading Devices Study - Melanopic Illuminance - Window Behind

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Electrochromic 18%

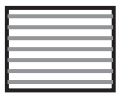
Room Depth: 70'-0"
Site Context: None

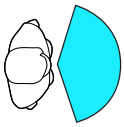




Shading Devices Study - Melanopic Illuminance - Window Left

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Electrochromic 18%
Room Depth: 70'-0"
Site Context: None

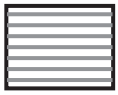


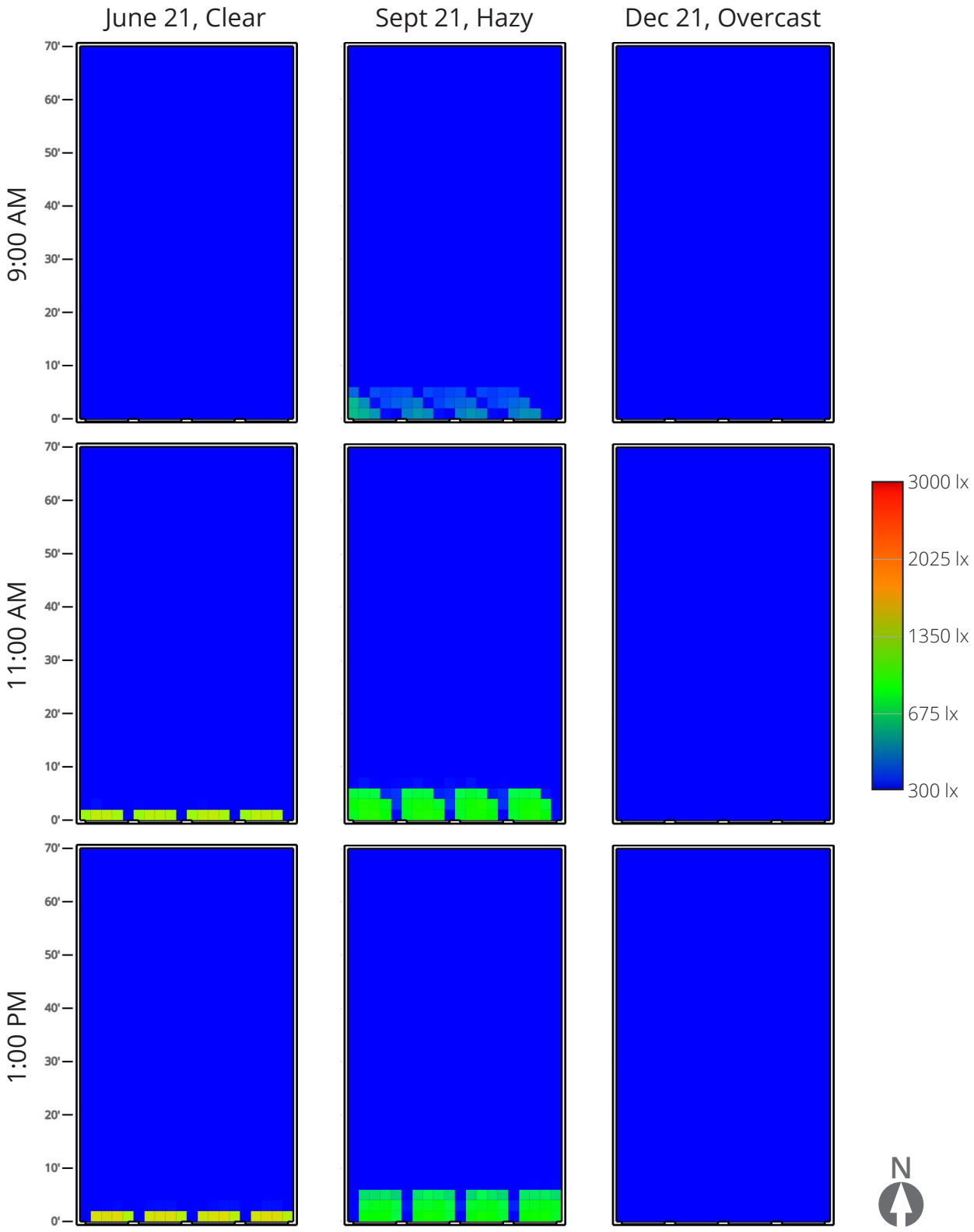


Shading Devices Study - Photopic Illuminance - Workplane Sensors

Building Orientation: South
Window Head Height AFF: 8’-0”
Shading Devices: Electrochromic 6%

Room Depth: 70’-0”
Site Context: None

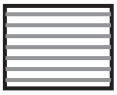


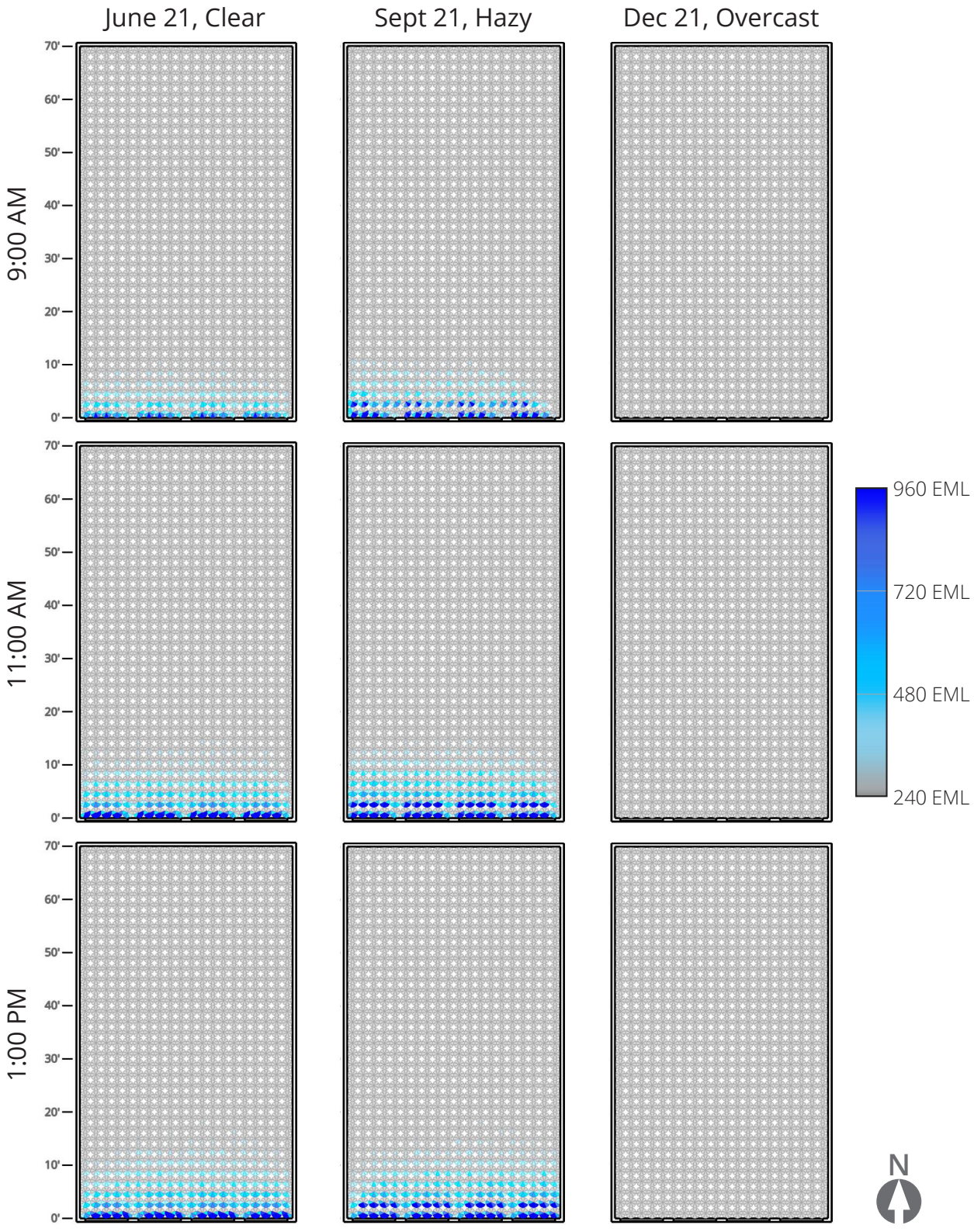


Shading Devices Study - Melanopic Illuminance - View Sensors

Building Orientation: South
Window Head Height AFF: 8’-0”
Shading Devices: Electrochromic 6%

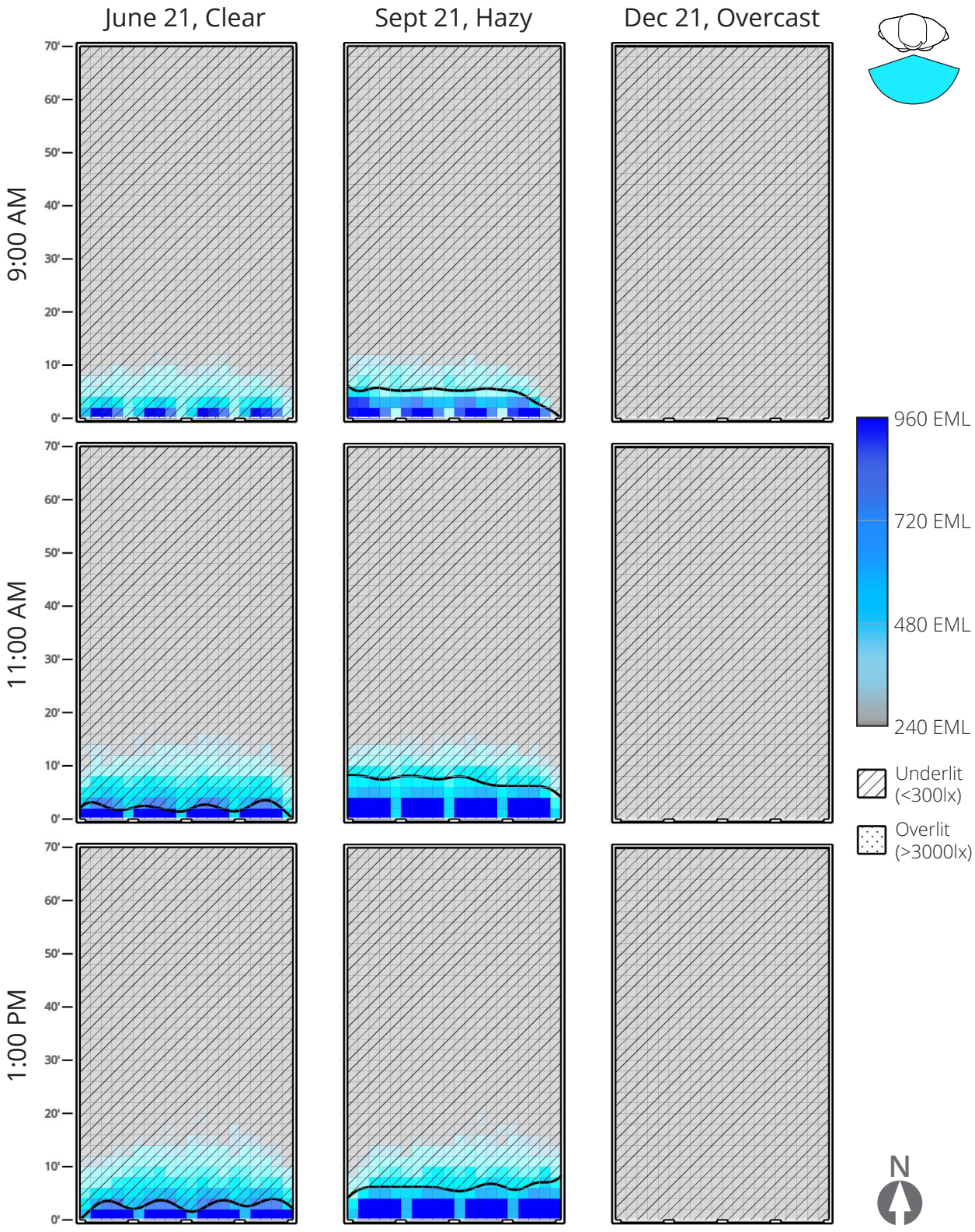
Room Depth: 70’-0”
Site Context: None





Shading Devices Study - Melanopic Illuminance - Window Front

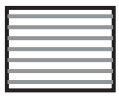
Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Electrochromic 6%
Room Depth: 70'-0"
Site Context: None

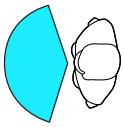


Shading Devices Study - Melanopic Illuminance - Window Right

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: Electrochromic 6%

Room Depth: 70'-0"
Site Context: None

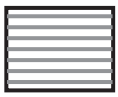


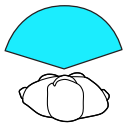


Shading Devices Study - Melanopic Illuminance - Window Behind

Building Orientation: South
Window Head Height AFF: 8’-0”
Shading Devices: Electrochromic 6%

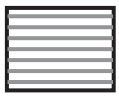
Room Depth: 70’-0”
Site Context: None

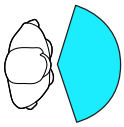




Shading Devices Study - Melanopic Illuminance - Window Left

Building Orientation: South
Window Head Height AFF: 8’-0”
Shading Devices: Electrochromic 6%
Room Depth: 70’-0”
Site Context: None

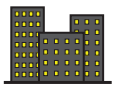


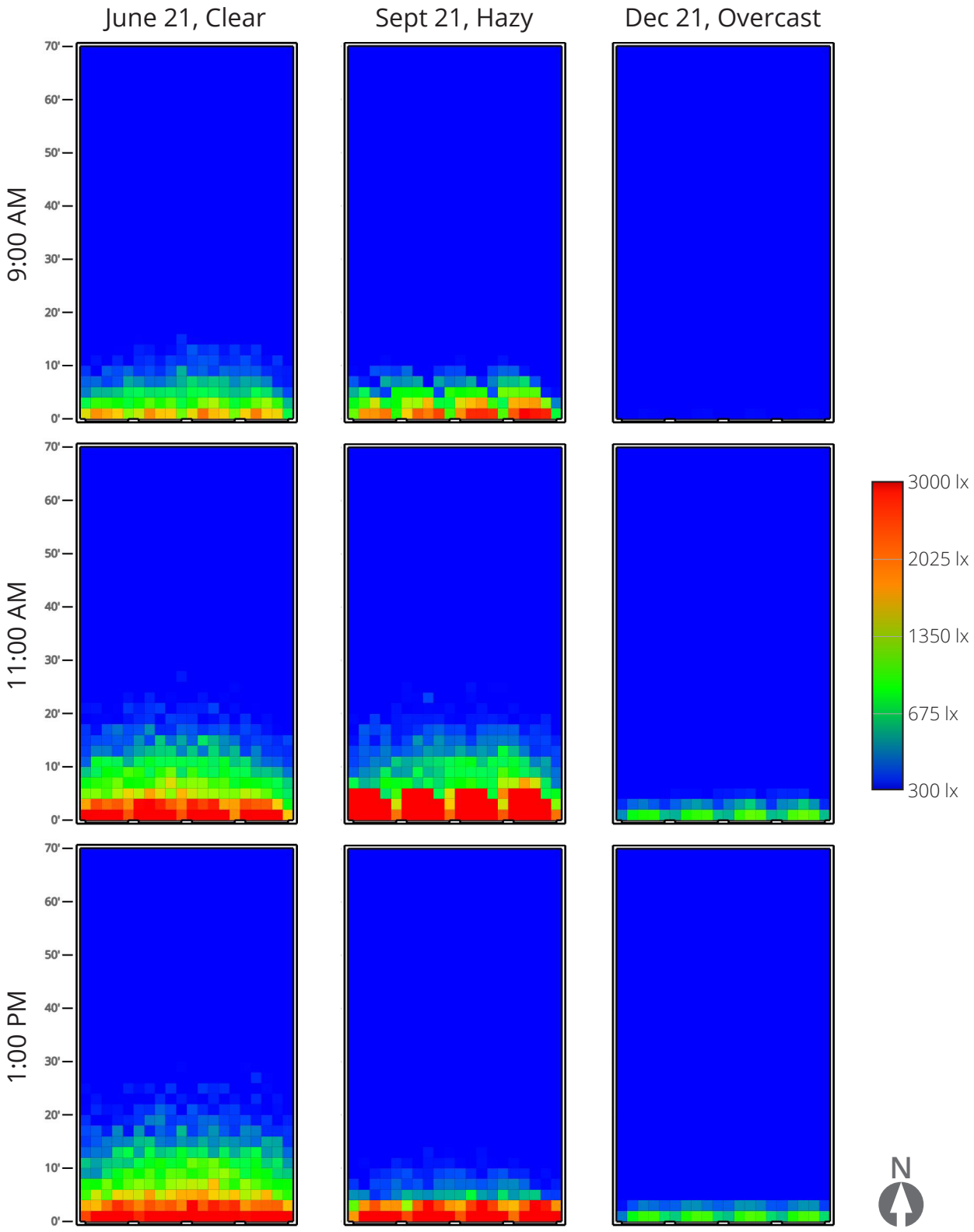


Visual Obstruction Study - Photopic Illuminance - Workplane Sensors

Building Orientation: South
Window Head Height AFF: 8’-0”
Shading Devices: None

Room Depth: 70’-0”
Site Context: Downtown Seattle

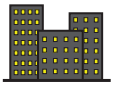


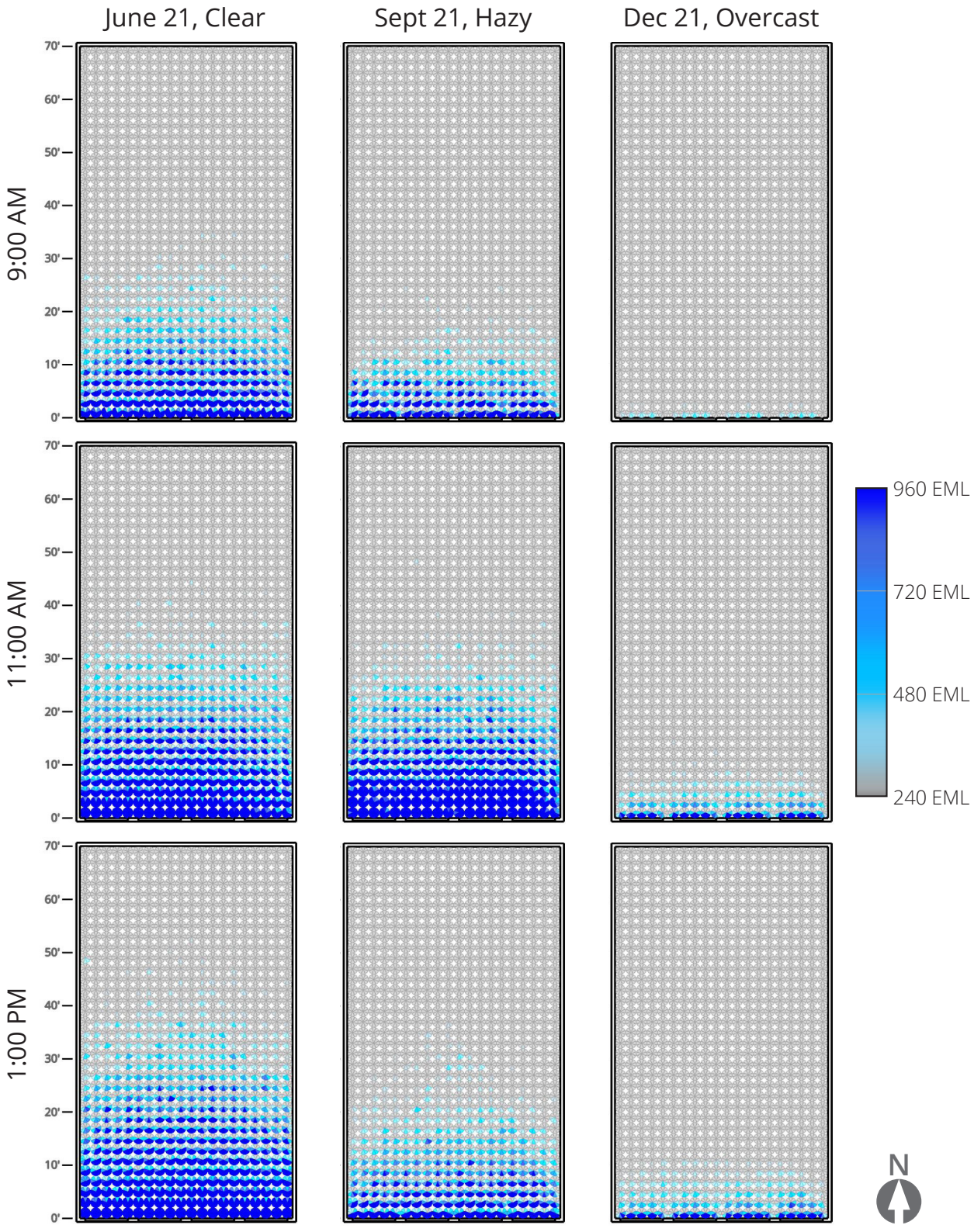


Visual Obstruction Study - Melanopic Illuminance - View Sensors

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: None

Room Depth: 70'-0"
Site Context: Downtown Seattle

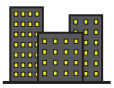


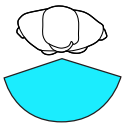


Visual Obstruction Study - Melanopic Illuminance - Window Front

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: None

Room Depth: 70'-0"
Site Context: Downtown Seattle

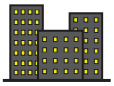


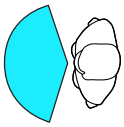


Visual Obstruction Study - Melanopic Illuminance - Window Right

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: None

Room Depth: 70'-0"
Site Context: Downtown Seattle

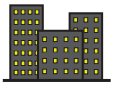


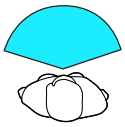


Visual Obstruction Study - Melanopic Illuminance - Window Behind

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: None

Room Depth: 70'-0"
Site Context: Downtown Seattle

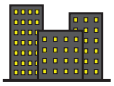


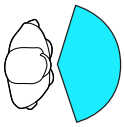


Visual Obstruction Study - Melanopic Illuminance - Window Left

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: None

Room Depth: 70'-0"
Site Context: Downtown Seattle

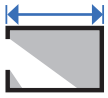


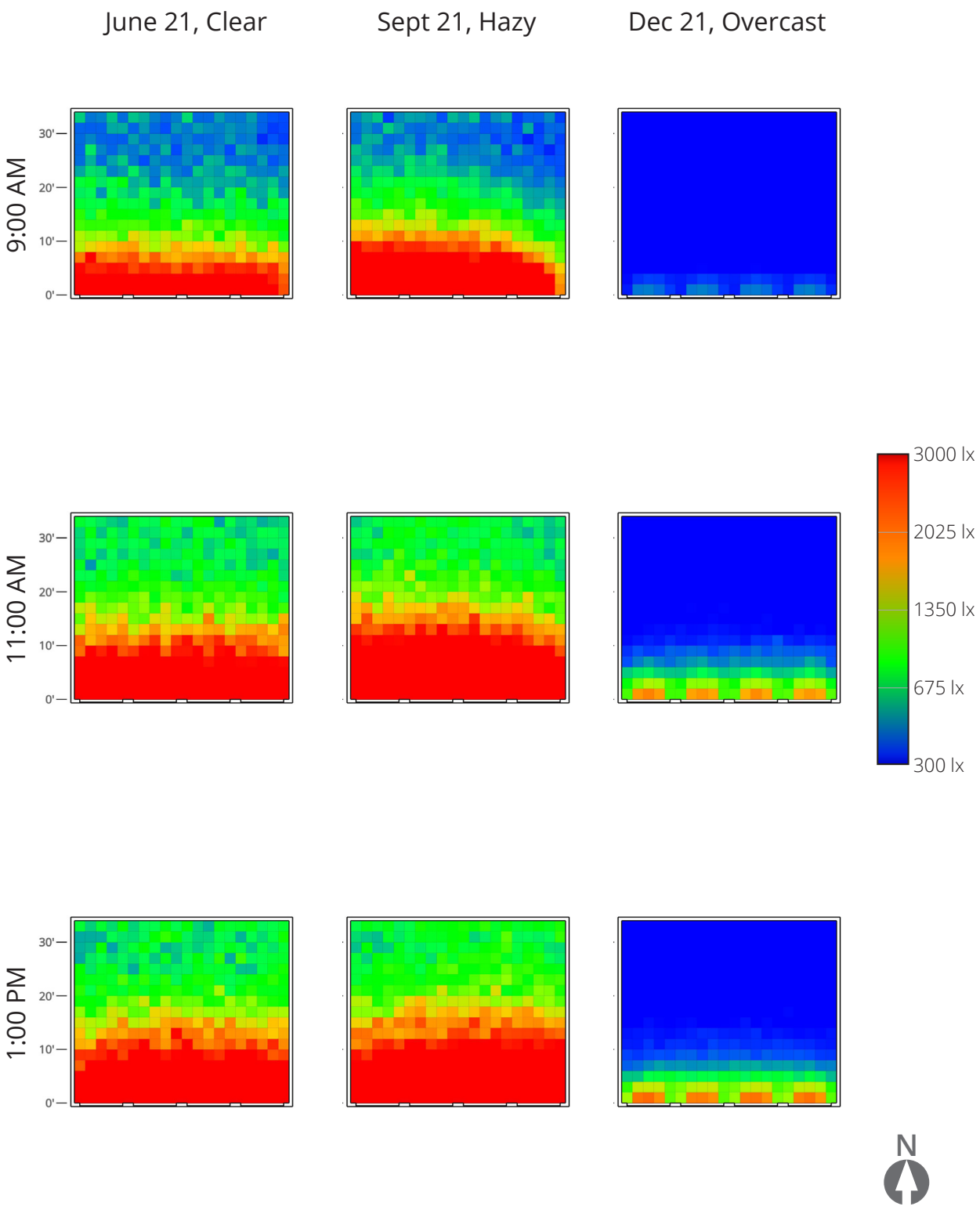


Room Depth Study - Photopic Illuminance - Workplane Sensors

Building Orientation: South
Window Head Height AFF: 8’-0”
Shading Devices: None

Room Depth: 34’-0”
Site Context: None

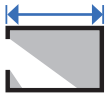




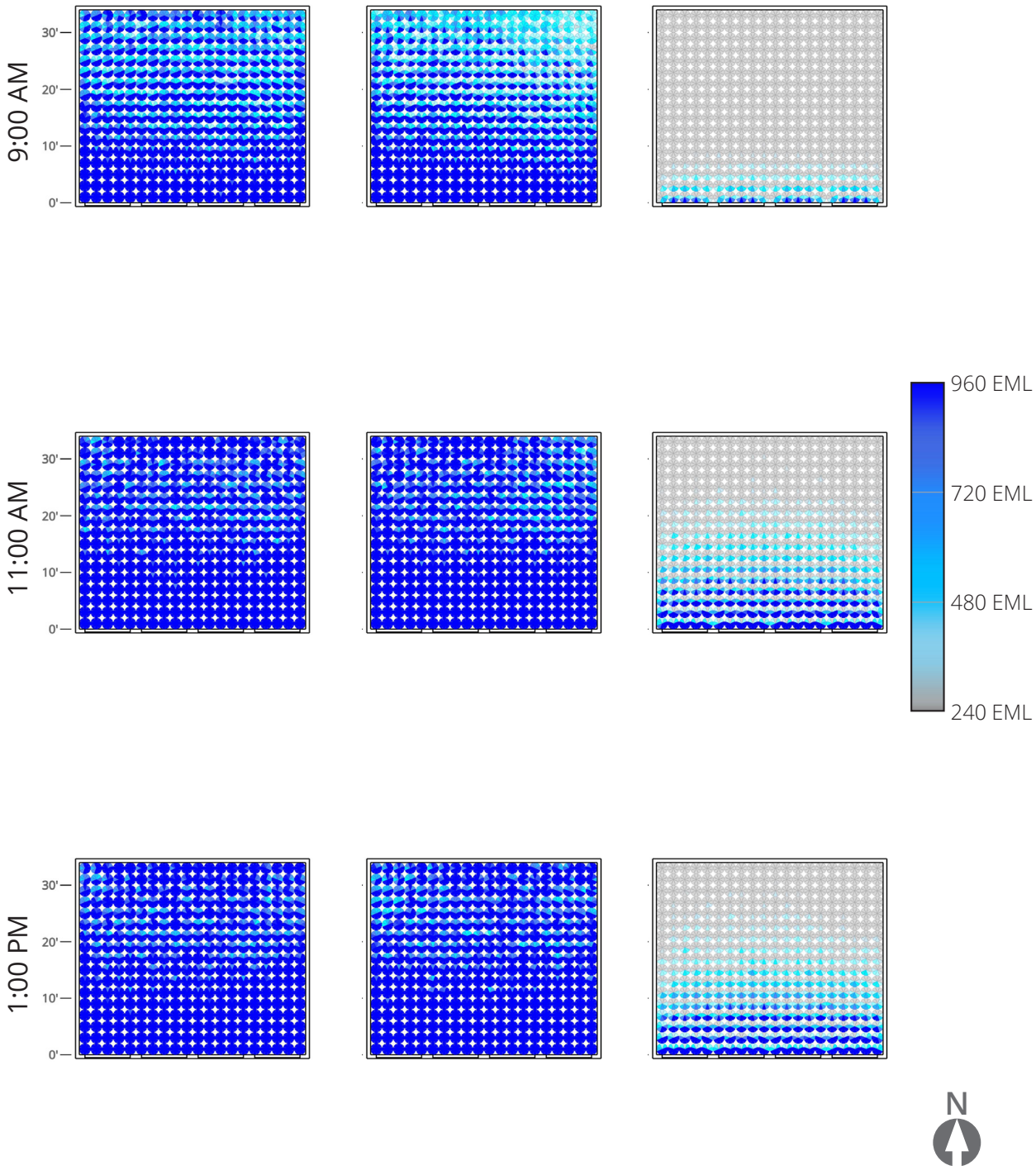
Room Depth Study - Melanopic Illuminance - View Sensors

Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: None

Room Depth: 34'-0"
Site Context: None



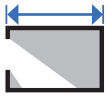
June 21, Clear | Sept 21, Hazy | Dec 21, Overcast

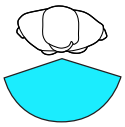


Room Depth Study - Melanopic Illuminance - Window Front

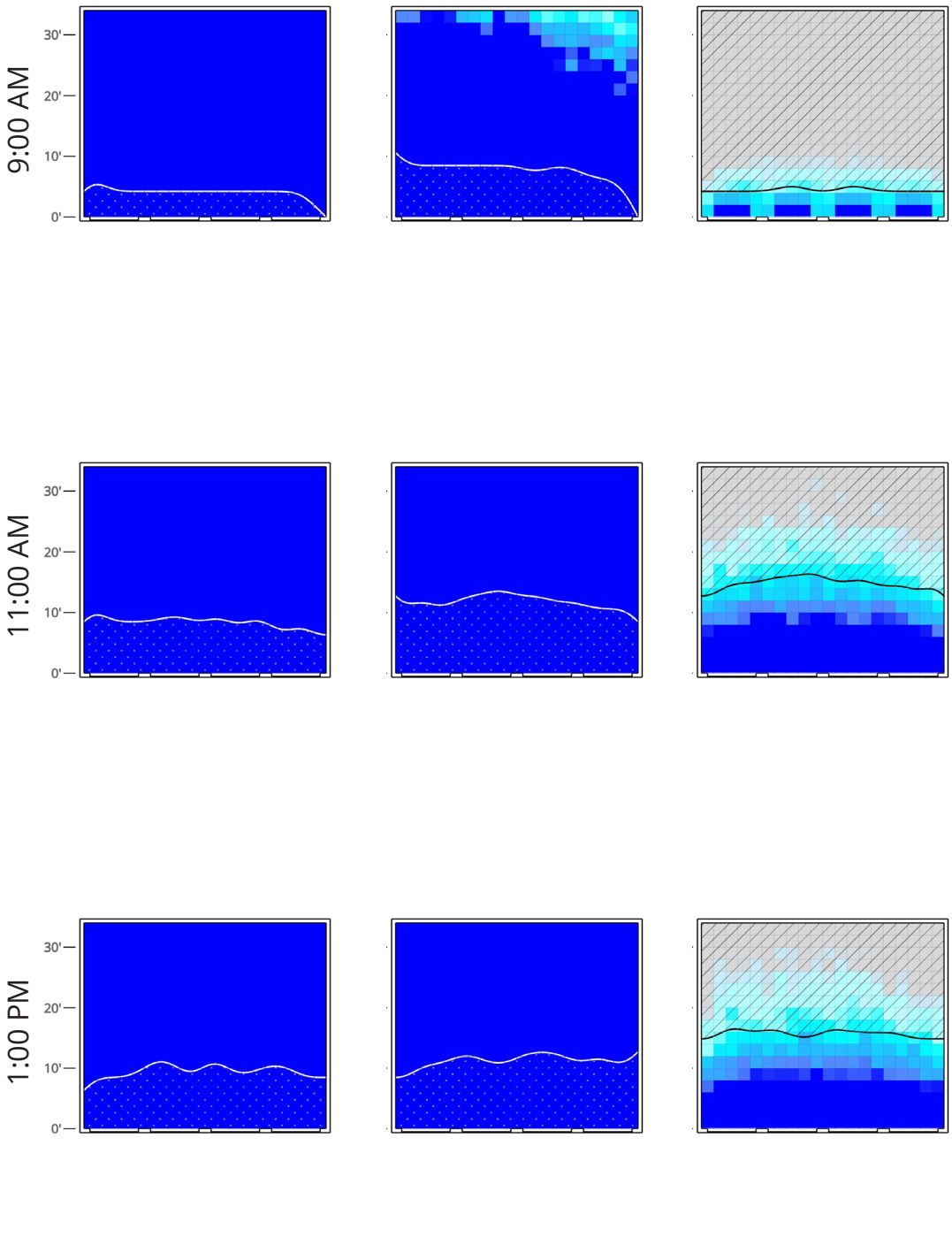
Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: None

Room Depth: 34'-0"
Site Context: None





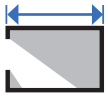
June 21, Clear | Sept 21, Hazy | Dec 21, Overcast

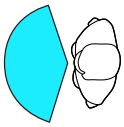


Room Depth Study - Melanopic Illuminance - Window Right

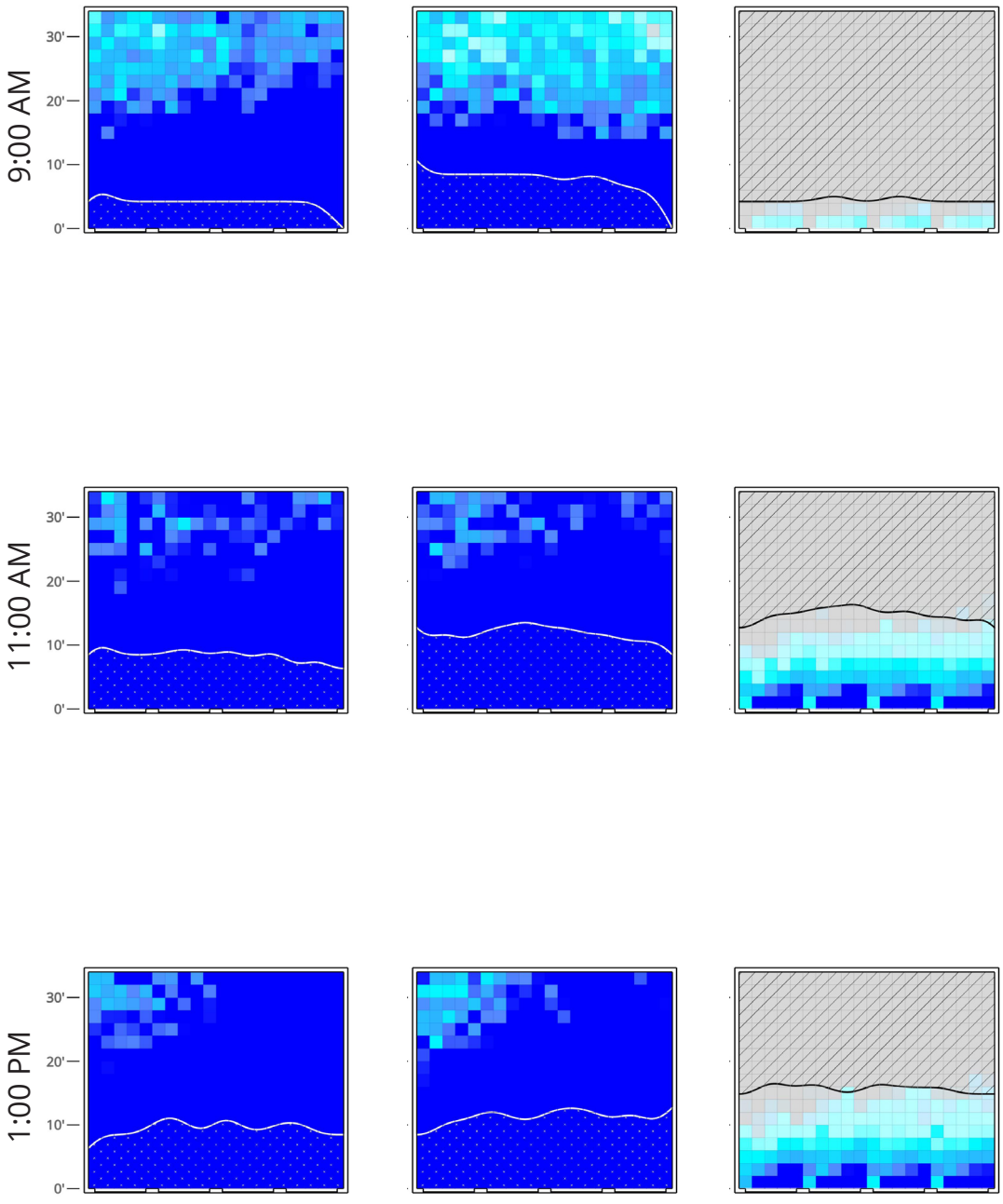
Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: None

Room Depth: 34'-0"
Site Context: None





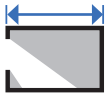
June 21, Clear | Sept 21, Hazy | Dec 21, Overcast

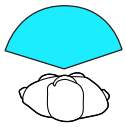


Room Depth Study - Melanopic Illuminance - Window Behind

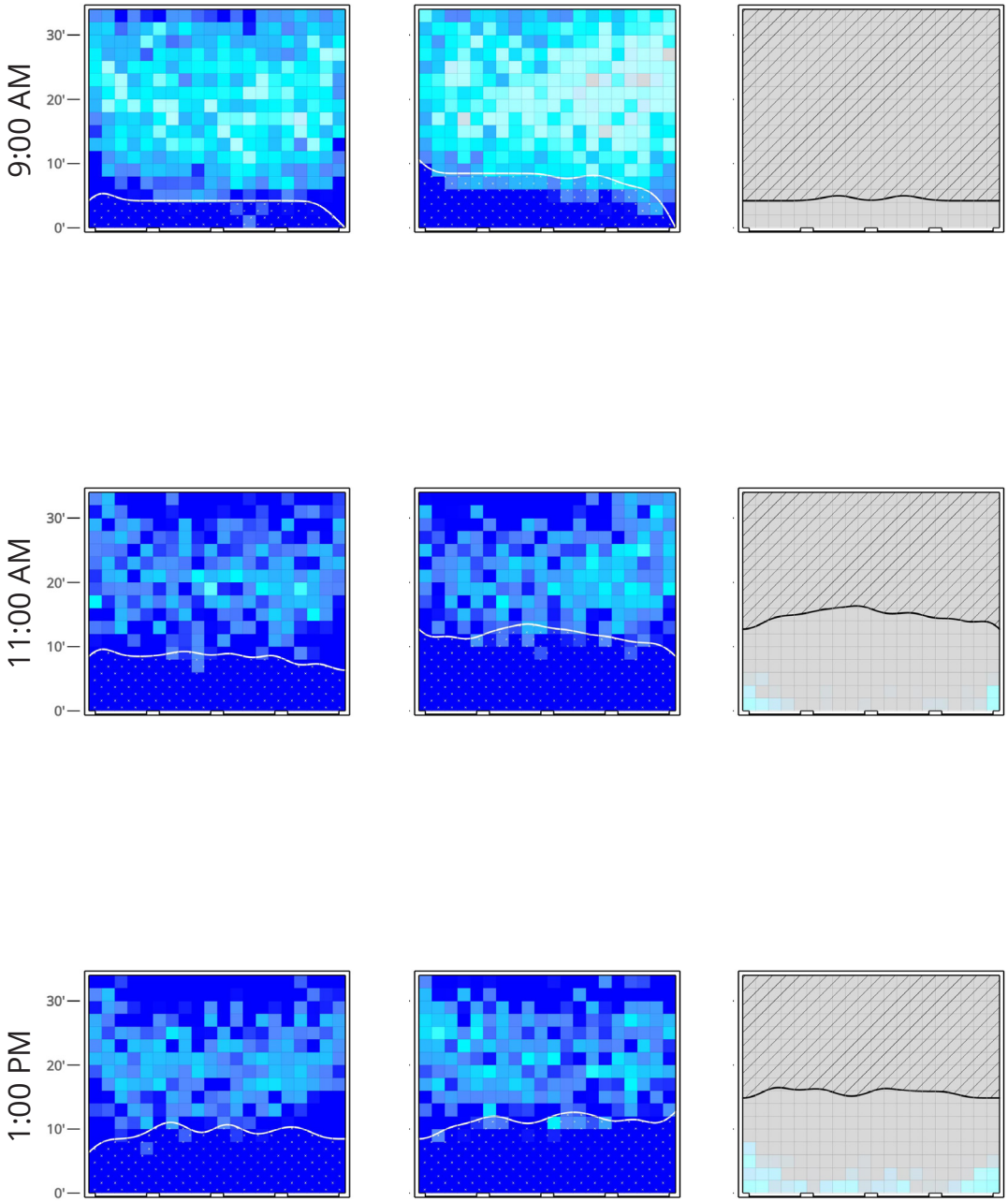
Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: None

Room Depth: 34'-0"
Site Context: None





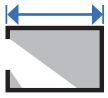
June 21, Clear | Sept 21, Hazy | Dec 21, Overcast

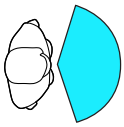


Room Depth Study - Melanopic Illuminance - Window Left

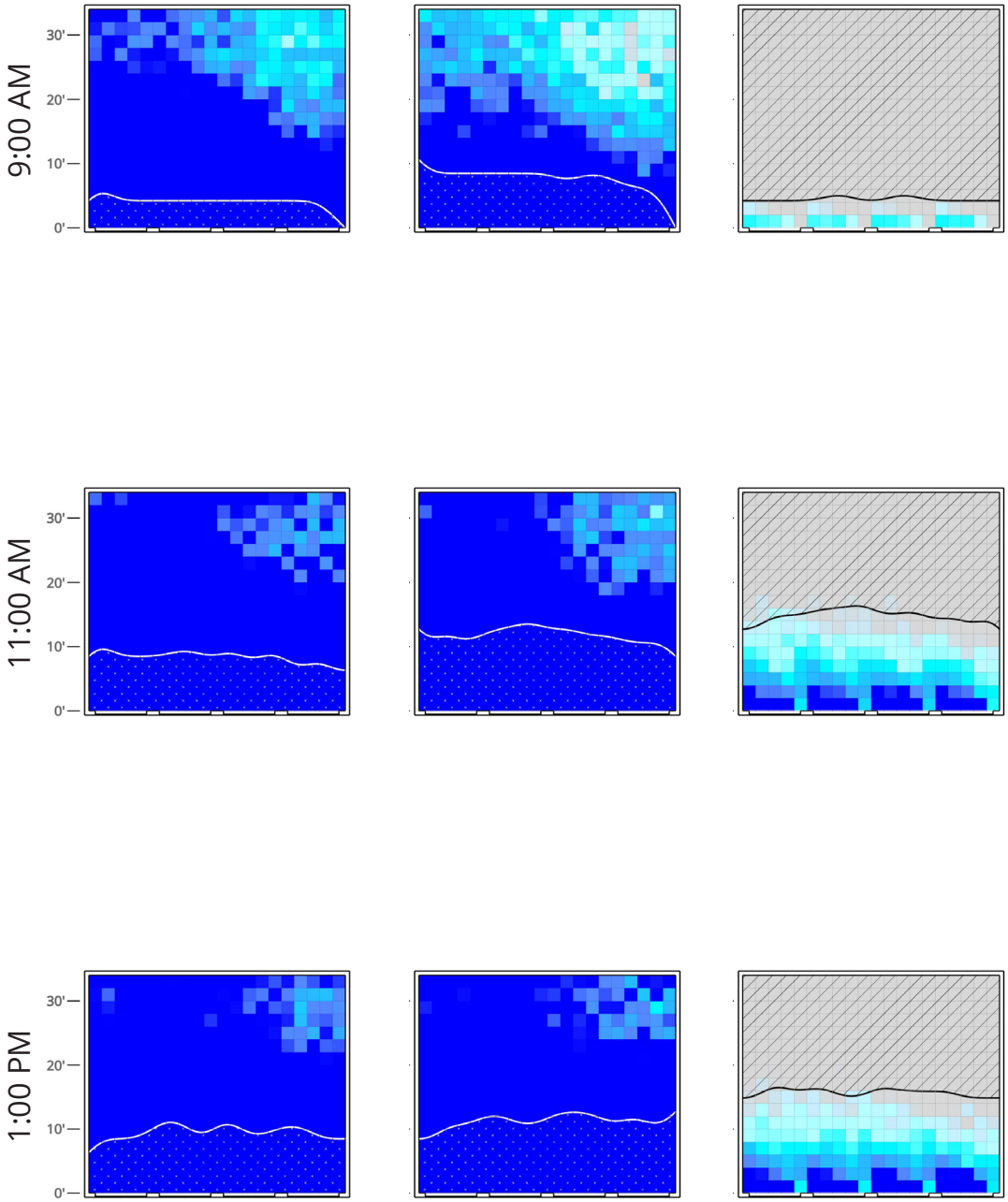
Building Orientation: South
Window Head Height AFF: 8'-0"
Shading Devices: None

Room Depth: 34'-0"
Site Context: None



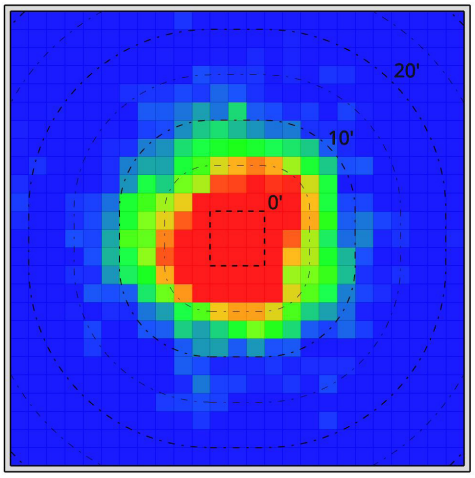


June 21, Clear | Sept 21, Hazy | Dec 21, Overcast

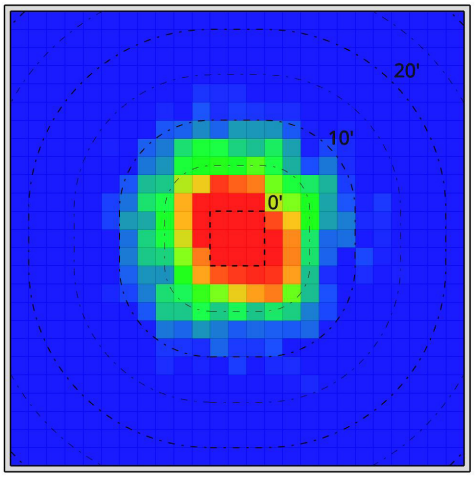


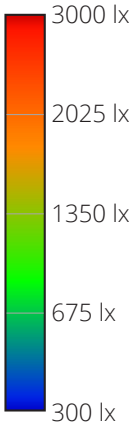
Skylight Study - Photopic Illuminance - Workplane Sensors

June 21, Overcast

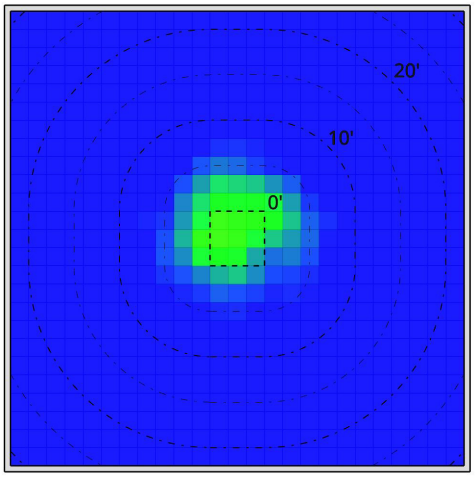


Sept 21, Overcast





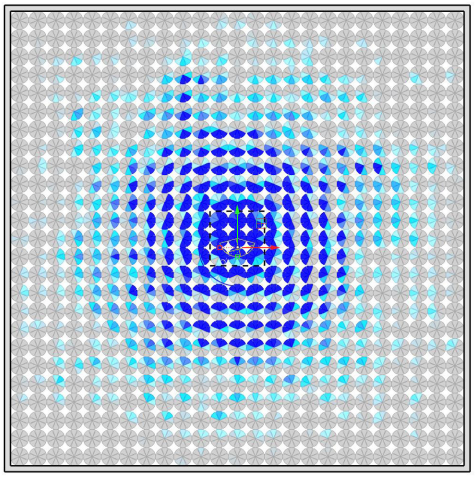
Dec 21, Overcast



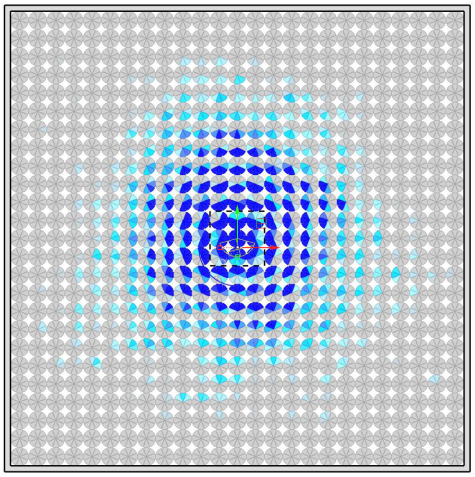


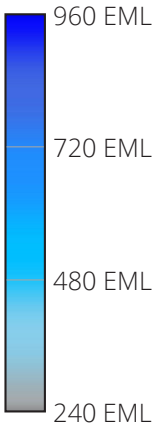
Skylight Study - Melanopic Illuminance - View Sensors

June 21, Overcast

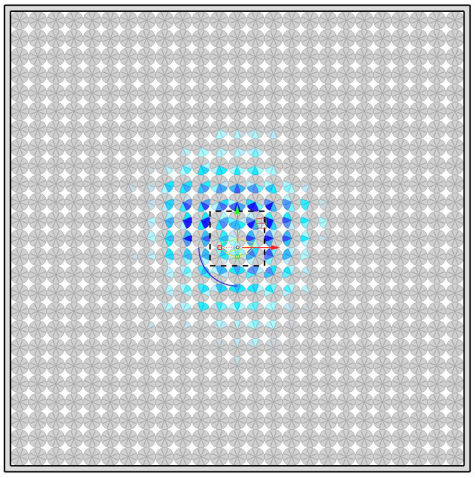


Sept 21, Overcast





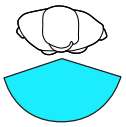
Dec 21, Overcast



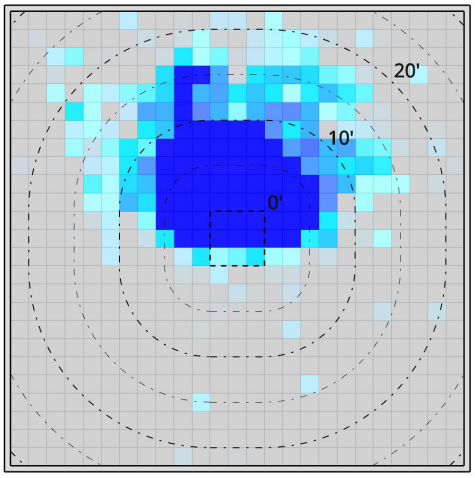


Skylight Study - Photopic Illuminance - Workplane Sensors





June 21, Overcast



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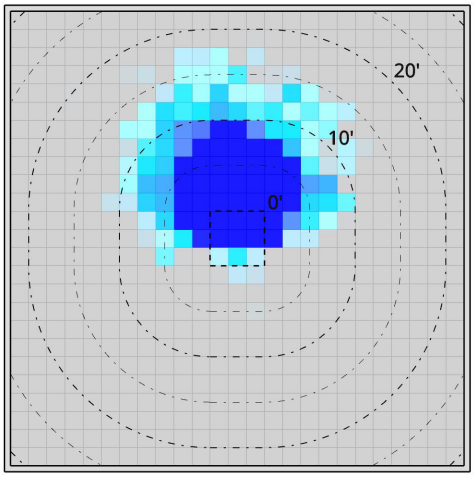

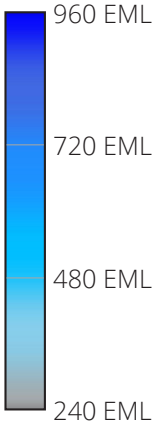

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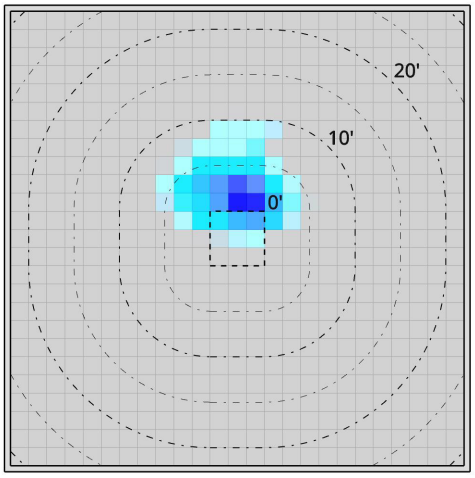
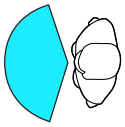




Skylight Study - Melanopic Illuminance - View Sensors





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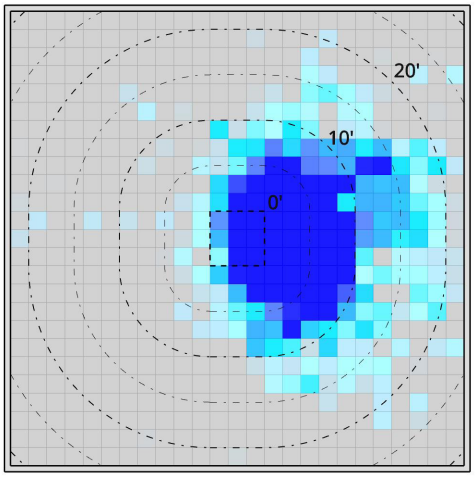

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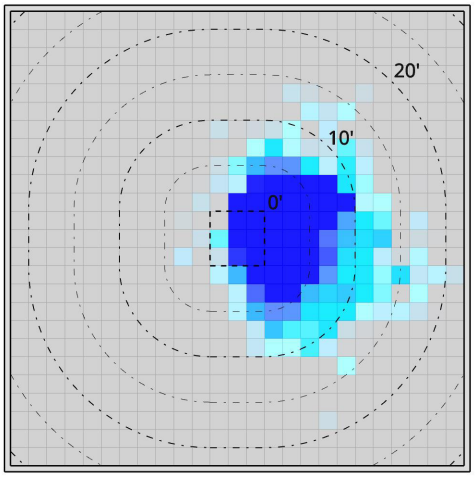

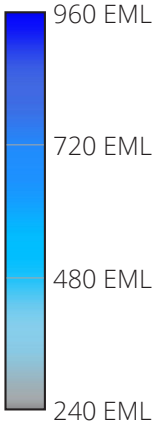

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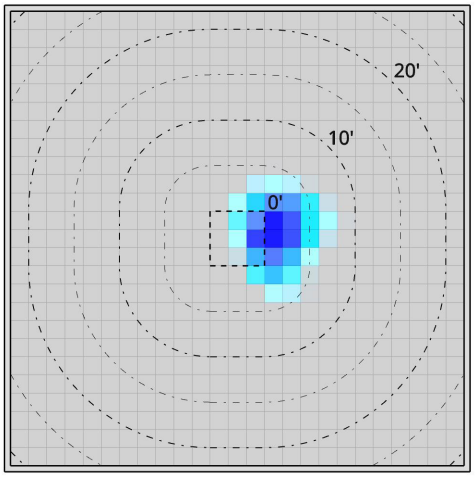
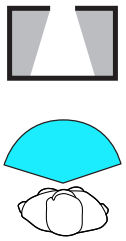




Skylight Study - Photopic Illuminance - Workplane Sensors



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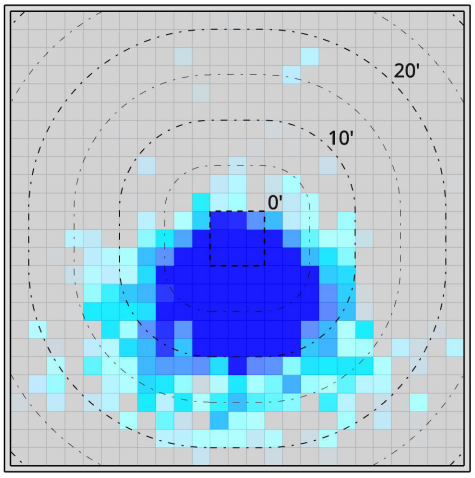

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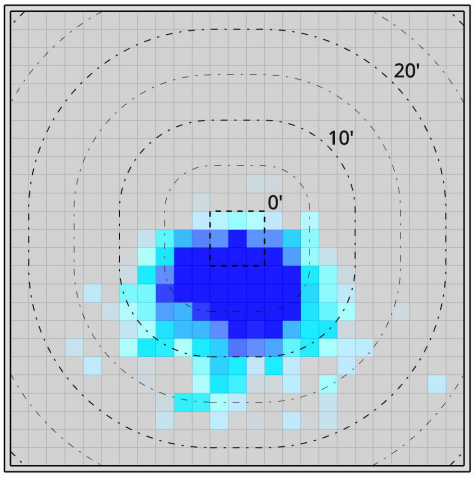

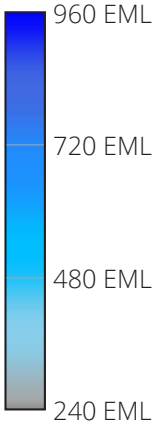

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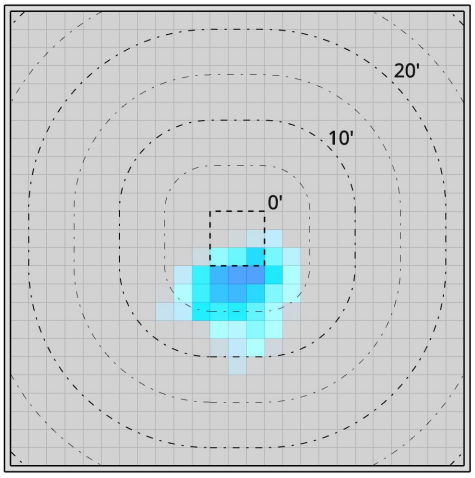
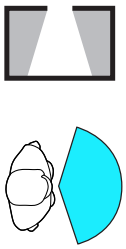




Skylight Study - Melanopic Illuminance - View Sensors



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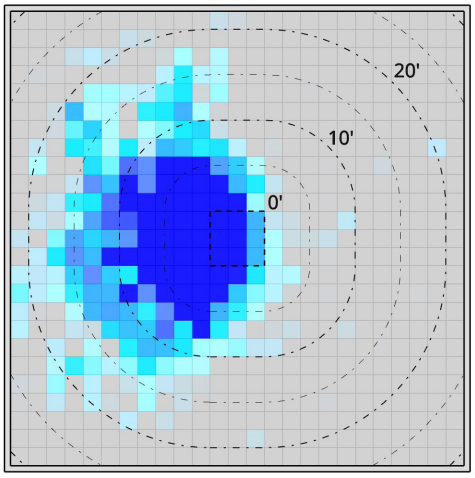

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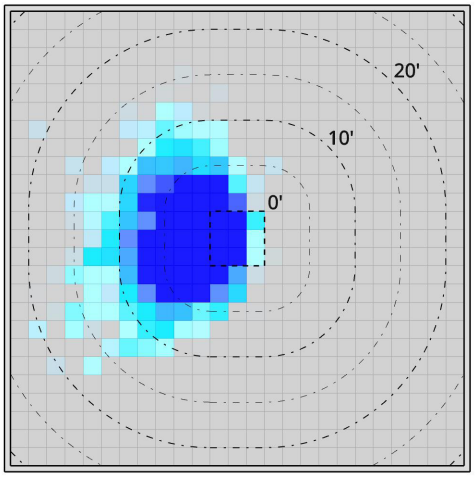

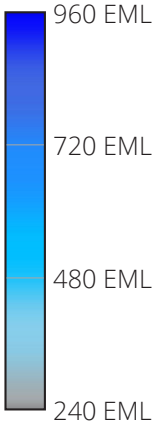

Dec 21, Overcast

