Comparing Occupant Light Exposure in Factory and Office Spaces

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INTRODUCTION

There is an increasing desire to provide healthy workplace environments that better serve people while minimizing the impact on the planet. Building recommendations help designers incorporate the latest research and best practices, but translating research studies conducted in different settings to broader recommendations is challenging. This is particularly true for lighting, with researchers continuing to learn more about circadian, neuroendocrine, and neurobehavioral responses to light. The recommendations are regularly adjusting to incorporate the latest research as well as feedback from practitioners implementing these recommendations. There remains a need to better document the actual light exposure that people experience over the course of a day and across seasons so that researchers can better understand the influence of light on people and recommendations can be refined. Thankfully, advances in sensor technology are making this more possible than ever.

Pacific Northwest National Laboratory (PNNL) collaborated with ETC Inc. to understand actual occupant light exposure in factory and office spaces at ETC headquarters in Middleton, WI. The primary building at ETC headquarters opened in 2004, and houses approximately 800 employees who contribute to central business functions, customer support, and research and development, as well as the company's primary 60,000 $ft.^2$ manufacturing facility. Vertical light exposure measurements, including electric light and daylight, were recorded in factory and office work areas at occupant eye height. This document focuses on lighting measurements collected in six factory and office locations across work location, season, and time of day. Ultimately, detailed lighting measurements could be coupled with employee feedback to the support development of satisfactory work environments.

FIELD EVALUATIONS

PNNL conducts field evaluations of advanced solid-state lighting systems to collect empirical data and document building owner and end-user experience with lighting systems. The evaluations produce independent, third-party data and recommendations for use in decision-making by lighting manufacturers, designers, facility managers, and other professionals. Real-world installations often reveal product limitations and application issues that are not apparent from laboratory testing. The evaluations include the gathering of feedback from everyday people who live, work, and play under the lighting systems in a variety of space types. For more information and additional resources, please visit ***energy.gov/eere/ssl/solid-state-lighting***.

Figure 1: Images of a Blue Iris Labs Speck. The miniature spectrometers were mounted to existing workstation partitions and stationary shelving throughout the office and factory work areas to record vertical lighting measurements. A screen capture of the Blue Iris data portal is shown on the right.

DATA COLLECTION

PNNL used miniature spectrometers, called Specks and which are developed by Blue Iris Labs, that were distributed in a variety of factory, research, and office work areas to record occupant light exposure. Measurements were recorded over 8 months, from August 2022 to March 2023. Employee surveys were administered three times during this same period to understand any seasonal variations in occupant satisfaction with workplace lighting and reported time spent outside when not at work.

Miniature Spectrometers

Spectrometers measure the spectral power distribution of light and from this, different metrics, such as illuminance, correlated color temperature (CCT), and circadian metrics can be calculated. The miniature spectrometers used in this study are shown in *Figure 1*. The Specks were calibrated by the manufacturer, Blue Iris Labs, in July prior to beginning data collection in August. They were rotated between three different office areas and three factory areas, with 10 distributed per area for approximately 2 to 4 weeks before being moved to a new area. The spectrometers recorded a measurement every 60 seconds. All spectrometers were temporarily attached to existing surfaces, such as cubicle partitions or stationary shelving. The spectrometers were mounted vertically at average standing eye height (54 in. above the finished floor) in the factory and at average seated eye height (48 in. above the finished floor) in the offices to reflect typical occupant eye height in each work area.

Factory and Office Work Areas

Electric Lighting and Daylighting

Both the electric lighting and access to daylight varied among all the spaces, as shown in *Figure 2*. Many of the spaces included in the study were located on the west side of the building with access to direct sun in the afternoon and early evening, as depicted in *Figure 3*. Factory A was located near windows with a view to the exterior. Factory B was located directly beneath a large skylight (approximately 30 ft. by 6 ft.) And Factory C was located between the rows of skylights. All work areas in the factory were lighted with fluorescent high-bay luminaires and fluorescent or light-emitting diode (LED) workstation-mounted 1×4 luminaires with local control. All office areas were located near windows with a view, but access varied from workstation to workstation. The office spaces were lit with pendant fixtures as well as indirect cove fixtures that were mounted to the top of the workstation partitions.

Middleton experienced cloudy or partly cloudy weather for approximately 65% of the 8-month data collection period. The remaining days were 15% clear and 20% rain or snow. December, January, and March were the least clear, with just five clear days across all 3 months.

Lighting Controls

Control of the general lighting in the building (e.g., factory high-bay fixtures, office pendants, and cove lighting) was largely automated by a timeclock, and the lighting was not dimmable or adjustable. Factory employees typically worked 6:00 a.m. to 3:00 p.m., four days a week and

Figure 2: Images of factory and office workspaces at ETC headquarters in Middleton, WI.

6:00 a.m. to 10:00 a.m. on Fridays with a second factory shift often operating between 3:00 p.m. and 9:00 p.m. During the study, the company decided to add weekend shifts for factory positions; however, the work presented in this report is focused on primary occupancy hours between Monday and Friday. Office employees arrived between 7:00 a.m. and 9:00 a.m. and left between 4:00 p.m. and 6:00 p.m., five days a week. Due to the variety of schedules, the general lighting was typically on between 5:00 a.m. and 10:00 p.m. Employees in the factory had local control over the desk-mounted luminaires. Manual blinds were only available in the office spaces. There were skylights throughout the factory with an ETC-designed mesh filter hanging below the skylights *(shown in Figure 2)*.

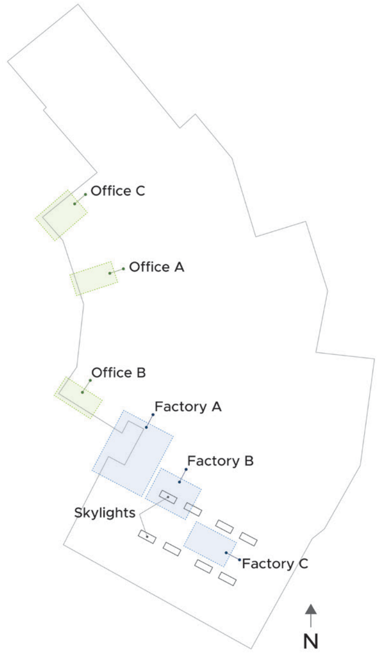

Figure 3: Layout of the three office and three factory spaces included in the study. All of the spaces with windows (Office A, B, and C and Factory A) are located on the west side of the building. Factories B and C are centrally located within the building under large skylights.

LIGHT EXPOSURE SUMMARY

Table 1 summarizes the workday lighting measurements for all six factory and office work areas. The vertical light levels in the factory were slightly higher than in the offices. Only 2% of measurements were below 50 lx. in the factory, compared to nearly 30% in the offices. Including daylight contributions, vertical illuminance remained below 150 lx. for 88% of the office employees' workday, while 60% of the factory measurements were greater than 150 lx. Each of the office spaces offered a similar distribution of illuminance levels; however, measurements above 300 lx. were recorded more frequently in Factories A and C compared to Factory B.

Less than 5% of the measurements collected in the factory had a CCT below 4000 K. The combination of electric light sources and daylight in the factory produced visually cooler CCTs compared to the office, where most measurements fell between 3000 and 4000 K., and very few measurements were above 5000 K.

		Percent of Measurements (%)							
		Factory				Office			
		A	B	C	TOT.	A	B	C	TOT.
Vertical Illuminance (lx)	< 50	< 1	5	2	**2**	25	31	33	**29**
	50 - 149	30	44	56	**38**	60	54	61	**59**
	150 - 299	43	47	21	**40**	14	11	5	**10**
	≥ 300	26	4	21	**20**	< 1	4	1	**2**
CCT (K)	0- 2999	0	< 1	0	**0**	10	4	5	**7**
	3000 - 3999	< 1	< 1	< 1	**0**	68	66	81	**71**
	4000 - 4999	66	58	97	**71**	16	27	13	**17**
	5000+	33	41	2	**29**	6	3	1	**4**
CS	≥ 0.30	29	8	20	**22**	2	3	1	**2**
m-EDI	≥ 136	41	30	31	**36**	4	8	3	**5**
	≥ 250	22	4	19	**17**	1	3	1	**1**

Table 1: Summary of all factory and office weekday measurements between 7:00 a.m. and 5:00 p.m. Factory A has access to west-facing windows and Factories B and C have skylights. All three offices have west-facing windows. The blue and green shading communicate the distribution graphically; darker colors mean that more measurements were recorded within a particular range.

Although neither the office spaces nor the factory spaces were specifically designed to achieve daytime light exposure recommendations outlined in UL DG24480[1] or the International WELL Building Institute Standard,[2] the cooler CCTs and higher illuminance levels in the factory spaces resulted in lighting conditions that tend to satisfy the design criteria more often than the office spaces. Two common circadian metrics referenced in the documents, circadian stimulus (CS) and melanopic equivalent daylight illuminance (m-EDI), were calculated within the Blue Iris Labs software and are used by some to estimate the potential of a light source to support circadian rhythms. Published guidance for day-active people recommends exposure to light providing the following:

- CS of 0.3 or greater during the day
- m-EDI of 136 or greater during the day (earns one point)
- m-EDI of 250 or greater during the day (earns three points)

In the factory spaces, 22% of workday measurements met the CS criteria, compared to just 2% of office measurements. Similarly, the m-EDI targets were more often achieved in the factory than in the offices—particularly in Factory A and Factory C.

Seasonal Variation

As seasons change, the varying sunrise and sunset times along with varying altitude of the sun influence how much daylight enters through building fenestrations. As expected, the most dramatic variation in vertical illuminance was found in Factory A between the August and December measurement periods. The time series data in *Figure 4* show that in December the electric lighting system provided around 200 vertical lx. or less and any daylight contribution rarely increased the illuminance level above 400 lx. In August, longer days and clearer skies increased illuminance levels in the Factory A space above 500 lx. throughout the entire workday. On average, illuminance at half

Figure 4: Sample of time-series data for all vertical measurement locations. All time-series plots begin on a Monday; the plots include weekends to show the difference between workdays and weekends.

of the measurement locations exceeded 1,000 lx. For approximately 55 minutes per day depending on the weather. Conversely, measurements recorded in Factories B and C were similar in the fall and early spring. Periods of increased illuminance in Factory C are due to the use of workstation-mounted luminaires.

In the offices, relatively minimal daylight contribution resulted in minor seasonal variation in lighting measurements except for longer or shorter days. Tall, thin peaks of illuminance can be seen on clear days regardless of the season; however, most measurements remain well below 200 lx. in these spaces. Data collection periods were overlapped for Offices B and C in March to compare office settings at the same time of year. Despite the variation in location and workstation layout of each office, the day-to-day measurements follow a nearly identical pattern, governed by static electric lighting, movement of the sun, and weather.

Daily Variation

Another dimension to understanding dynamic light exposure from the occupant perspective is the daily variation that may not change much seasonally in some work areas but will change throughout the day and over the seasons in other areas, as shown in *Figure 5*. Illuminance levels in Office B in the winter rise and fall between sunrise and sunset, approximately 7:30 a.m. to 4:30 p.m. In the spring, illuminance levels steadily climb over the day and are still increasing during the

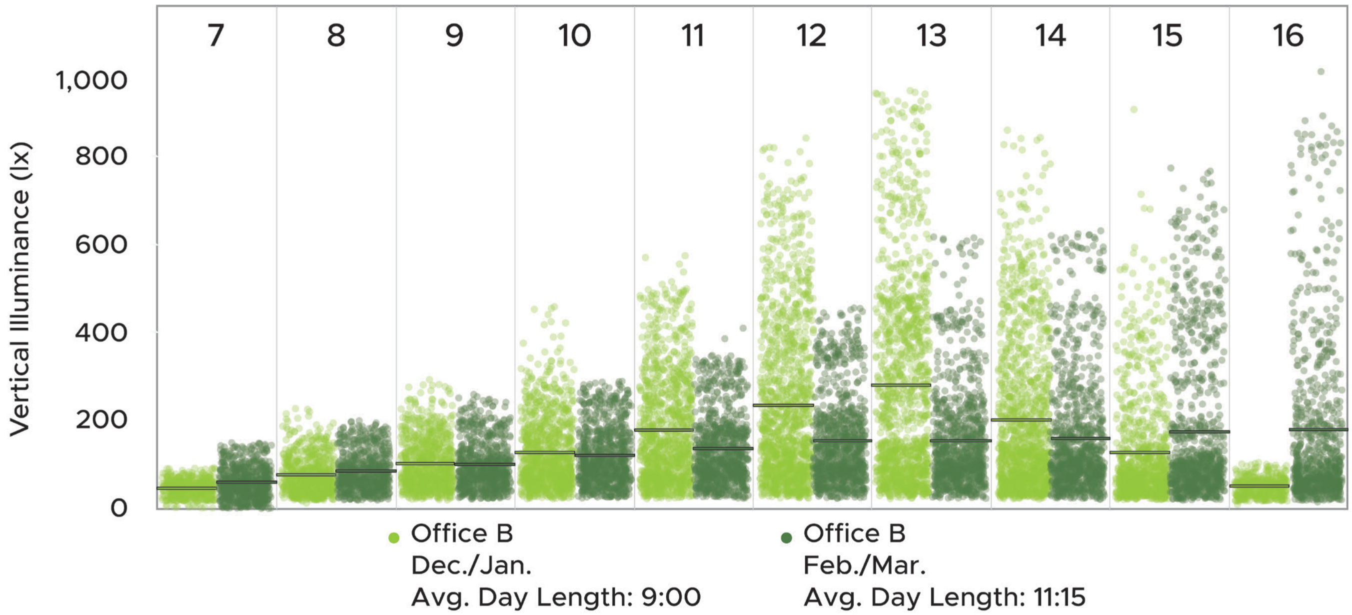

Figure 5: Hourly vertical illuminance measurements from all spectrometers in Office B. The lines across each hour represent the average measurement.

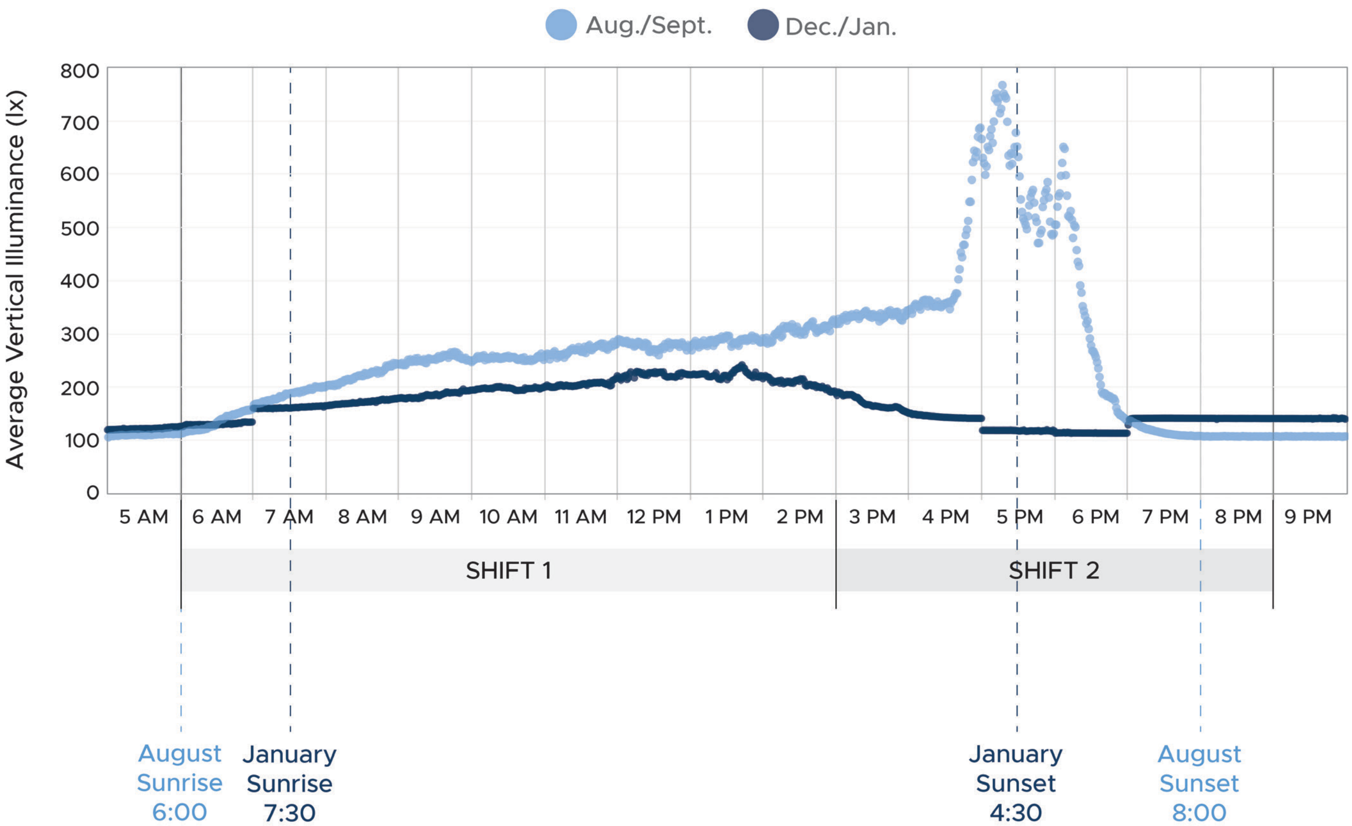

Figure 6: Average vertical illuminance on weekdays for all 10 spectrometers deployed in Factory A in the summer and winter.

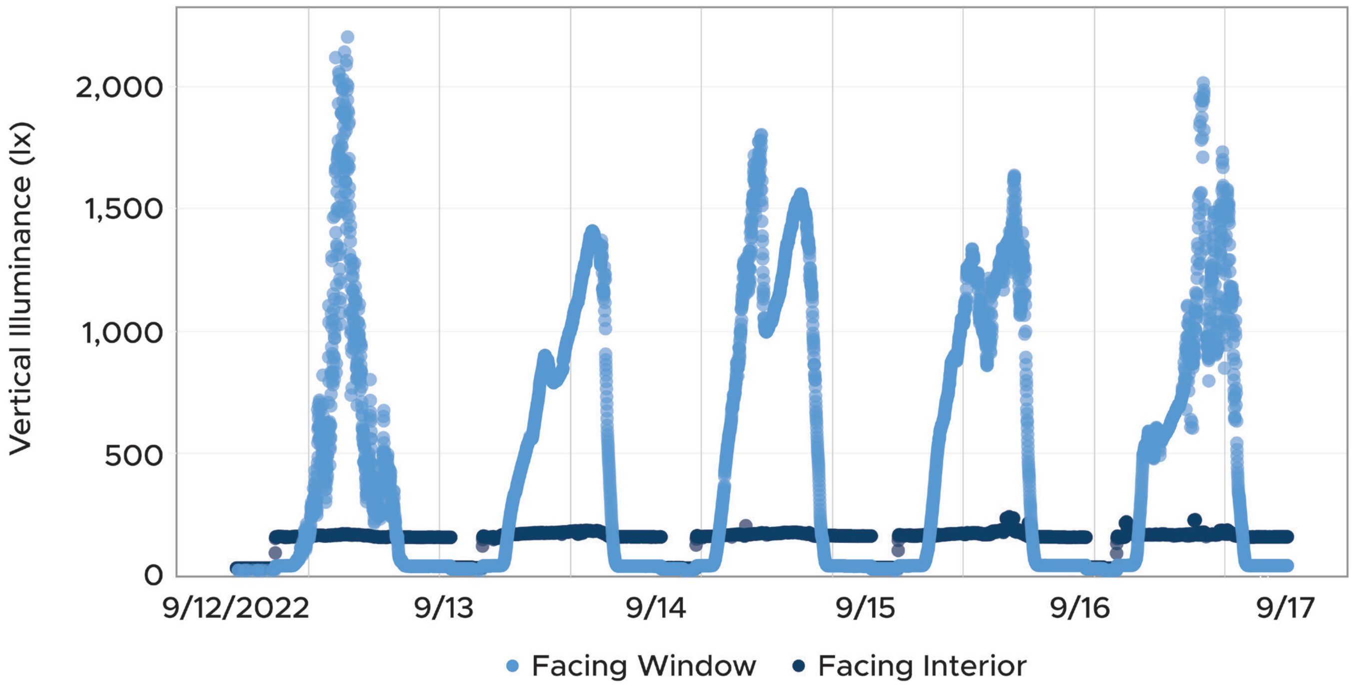

Figure 7: Vertical illuminance summary for two workstations along a window wall in the factory in September. One workstation faces the windows (light blue) and the other workstation faces teh interior of the building (dark blue).

4 o'clock hour when office employees are finishing their work. During both seasons, the vertical illuminance levels in the morning are more uniform compared to the afternoon hours due to the west-facing windows. Increased illuminance levels in the winter months due to the lower solar angle resulted in greater daylight penetration into the office. Even though there was more available daylight in February and March, longer day length does not guarantee that all building occupants will receive more light at their workstation.

The factory operates on two shifts from 6:00 a.m. to 3:00 p.m. and 3:00 p.m. to 9:00 p.m. *Figure 6* shows the average vertical illuminance measured by all sensors in Factory A during each data collection period in August and December. During the first shift, employees arrive as the sun is rising in August and the available daylight is immediately noticeable compared to the winter, when the sun does not rise until 7:00 – 7:30 a.m. During the winter, an electric light source is turned on. Light levels are largely similar throughout the day with slightly higher average illuminance levels provided in the summer. Around 2:00 p.m. or 3:00 p.m., the average light levels seasonally bifurcate as the sun begins to set in the winter and enter the west-facing windows during the summer. If the second shift is working, employees either enter a bright, daylit space in the summer or a comparatively dim factory space lit by electric sources after the sun has set in the winter.

Workstation to Workstation Variation

Within a given workstation, a simple shift in view direction can considerably change light exposure. In Factory A, two spectrometers were located next to each other, with one facing the window and one facing away from the window to represent multiple orientations at the same workstation. *Figure 7* shows that even though the spectrometers were only 12 in. apart, the recorded vertical illuminance levels were vastly different due to view direction. During the day, the spectrometer facing the window measured between approximately 50 and 2,000 lx. while the measurements recorded by the spectrometer facing the room only varied between 140 and 220 lx.

Considering factors like weather and daylight penetration in addition to view direction further complicates the variability of light in the vertical

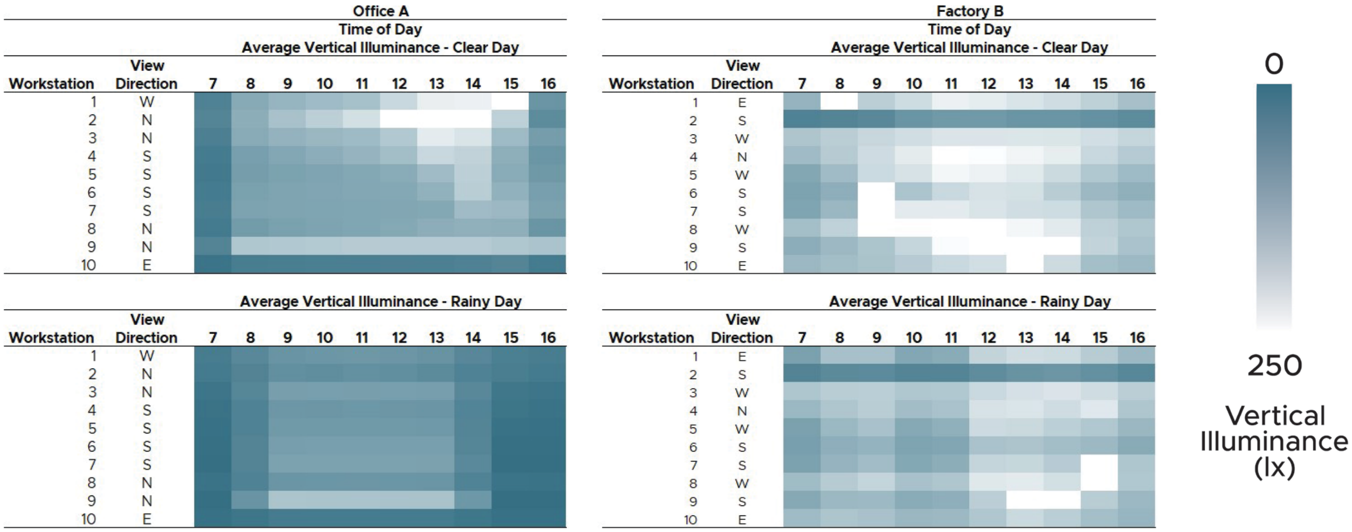

Figure 8: Average vertical illuminance in Office A (left) and Factory B (right). Average hourly measurements from each workstation with a spectrometer are presented for one clear day and one rainy day. Darker colors represent lower vertical illuminance levels. In both locations, workstation 1 is closest to windows or skylights and 10 is farthest from windows or skylights.

plane in buildings. *Figure 8* shows an example of a clear day and a rainy day in Office A with west-facing windows and Factory B with skylights. Overall, the skylights in the factory provided a brighter experience throughout the day regardless of the weather compared to the office. Workstations numbered 1 to 10 in each installation are arranged so that workstation 1 is located nearest to the windows or skylights and workstation 10 is the farthest. In the office, the spectrometers in workstations 1 and 2 are equidistant from the windows but are facing different directions and therefore receive unique light exposure on a clear day. Diminishing daylight penetration can be seen in the afternoon at workstations 3 through 7 in the office on a clear day. The spectrometers in workstations 9 and 10 are farthest from the windows and only receive electric light contribution from the overhead fixtures on clear and rainy days. The spectrometer located in workstation 9 is mostly capturing light from a cove fixture on top of the workstation partitions. On overcast or rainy days, the average illuminance in the offices is relatively consistent for all sensors over the workday.

In Factory B, even workstations farthest from the skylights, such as workstation 9, received similar light levels to workstations located directly beneath the skylight, such as workstation 3. Although workstation 2 is located very close to the skylight on a floor plan, the vertical illuminance is relatively low because it is facing away from the skylights toward a corridor. Other workstations facing south, such as workstations 6 or 7 are facing the skylight, which greatly increases the average vertical light levels on clear days. Higher light levels can be seen at most workstations between 9:00 a.m. and 3:00 p.m. on a sunny day under the skylights compared to rainy days.

Light and Health Metric Variation

Timing of light exposure may be particularly important for understanding influence on occupant well-being. Published guidance[2] recommends that light meeting the previously stated WELL design criteria be delivered to the eye of the occupant for at least 4 hours during the day beginning by noon at the latest. Due to abundant daylight in August, Factory A met the design criteria more frequently than any other space. However, with primarily west-facing windows near all the measured locations, the late afternoon sun and accompanying higher illuminance levels that satisfy the criteria often occur at the end of the workday for office employees and after some factory employees have departed.

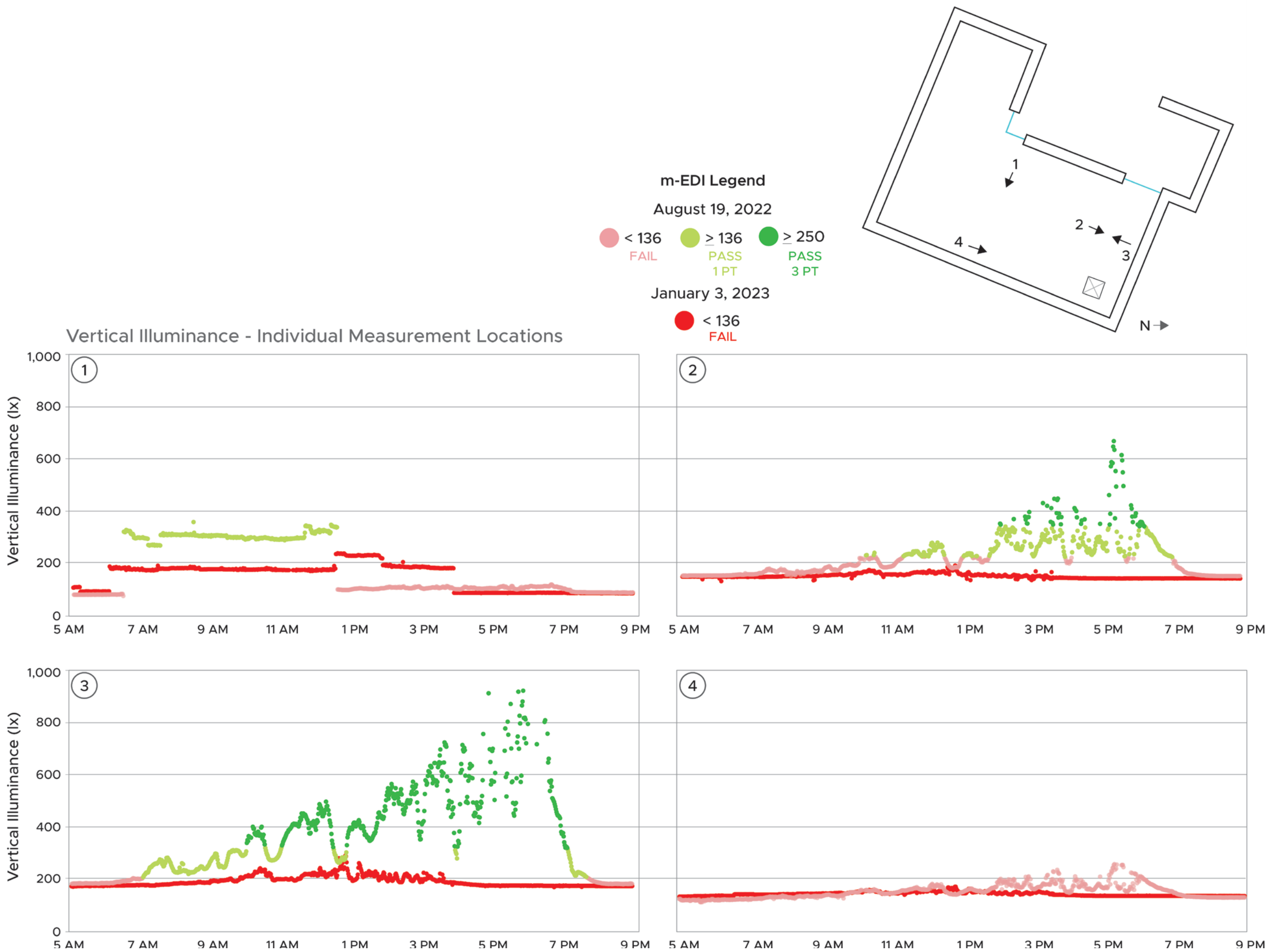

Figure 9: Comparison of vertical illuminance at four workstations in Factory A on August 19, 2022, and January 3, 2023. The color coding relates to the m-EDI value where the red and pink values are not meeting design criteria and both shades of green are meeting the recommendations.

To satisfy the recommended design targets, vertical measurements must meet or exceed 136 m-EDI to gain one point toward WELL Building Standard Building Certification while three points are given for exceeding 250 m-EDI. In January, none of the four workstations shown in *Figure 9* receive enough vertical illuminance to meet either m-EDI threshold. In August, proximity to windows and primary view direction influence how often the threshold of a particular workstation is met. For example, the spectrometer at workstation 1 is located closest to the windows but is facing away from the window, toward the building interior. The uniformity of the measurements suggests that the spectrometers are mostly recording unchanging overhead electric lighting compared to the dynamic nature of daylight contribution. The changes in intensity are due to the use of workstation-mounted luminaires. When the workstation-mounted luminaire is on, the increased intensity provides enough light to meet the one-point WELL recommendation for several hours during the morning. Similarly, the spectrometer at workstation 4 is located away from the windows and without occupant use of the workstation-mounted luminaire, the lighting at this workstation never reaches the m-EDI threshold.

Spectrometers at workstations 2 and 3 face each other at the same distance from the windows. In August, both receive substantial daylight contribution throughout the day—beginning at noon or 7:00 a.m., respectively. For workstation 2, light levels that meet the m-EDI threshold are only available in the afternoon compared to workstation 3, which receives light levels meeting the WELL recommended threshold all day.

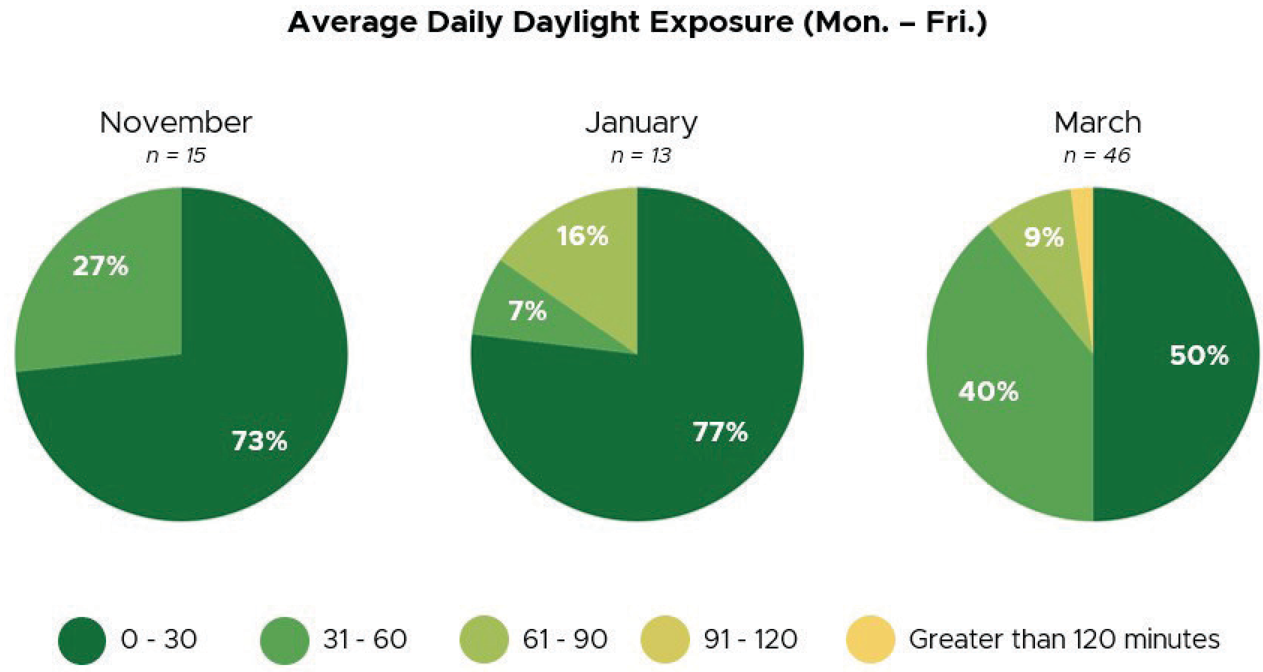

Figure 10: Average daily time spent outdoors for office and factory workers during the work week. During all three time periods, most participants reported spending between 0 and 30 minutes per day outdoors exposed to daylight.

TIME SPENT OUTDOORS

In addition to known shifts between seasons and over the course of a day, architectural characteristics such as exterior louvers, blinds, and room finishes all influence the light that is ultimately received at the eye of an occupant. Even with advanced measurement and modeling techniques, these factors are challenging to account for when trying to understand the light reaching the eye of an occupant. The spectrometers for this study were fastened to fixed architectural surfaces, but still differ substantially from actual light exposure received at the eye as the occupant moves from one environment to another. Additionally, documenting light exposure at work only represents a fraction of a person's 24-hour environment. To better understand light exposure outside of work, employees were asked to estimate their average time spent outdoors in November, January, and March. *Figure 10* shows that most respondents spent between 0 and 30 minutes per day outdoors.

TAKEAWAYS

Efficient application of daylight and electric light should always consider how to deliver the right amount and quality of light to the right place at the right time. While defining the appropriate lighting solution is challenging in itself, the measurements collected at the ETC headquarters highlight that occupant light exposure is difficult to predict due to varying daylight and weather conditions as well as occupant behaviors. The measurements demonstrate how seasonal variation impacts the lighting conditions in a space, suggesting a role for seasonal exposure recommendations that align with reduced daylight availability in winter months. While work needs and space limitations sometimes dictate view position and access to daylight, increasing the flexibility of view direction to accommodate varying lighting needs and preferences should be considered.

By leveraging new spectrometer technology, over 3 million measurements were recorded to better understand occupant light exposure in real factory and office work environments.

Lighting measurements in real work settings help researchers, designers, space planners, and facility managers consider the dynamic nature of light in the built environment over the course of a day and throughout the year as the research and recommendations for healthy workplaces progress.

ACKNOWLEDGMENTS

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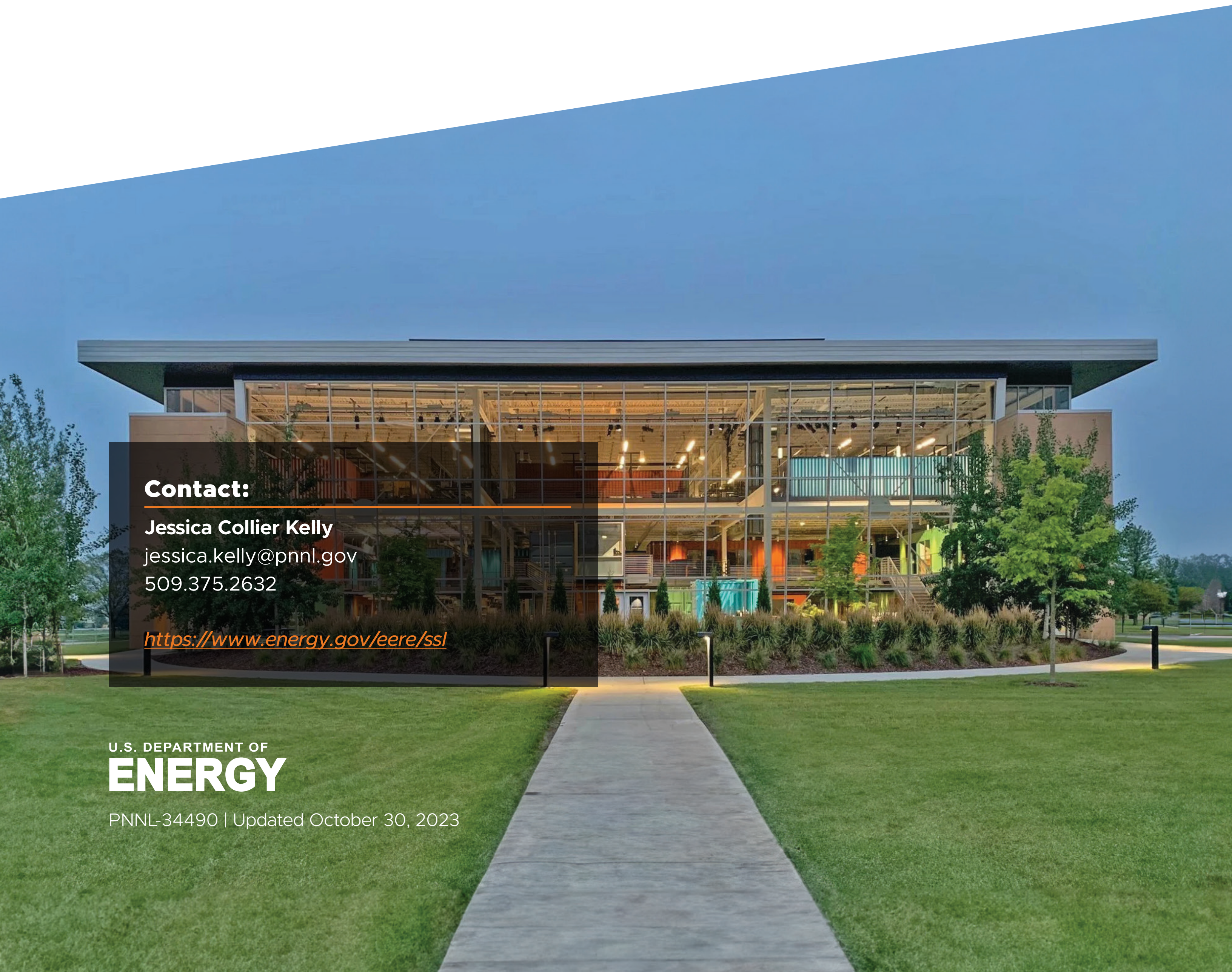
RESOURCES

1. UL. DG 24480. 2019. *Design Guideline for Promoting Circadian Entrainment with Light for Day-Active People*. Edition 1. Northbrook, IL.
2. IWBI – International Well Building Institute. 2023. *WELL v2TM Q1-Q2 2023 Lighting Feature L03*. https://v2.wellcertified.com/en/wellv2/overview.



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