WELL V2:

EVIDENCE BEHIND THE LIGHT CONCEPT

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Introduction:

The research is clear. The places where we spend our time have a huge impact on our overall health and well-being. Dive into our compilation of research digests to learn how the places we create today can impact our health tomorrow.

Our compilation of research digests directly compliment the WELL Building Standard, providing a deeper dive into the evidence behind each feature. Focused on the WELL concepts, the digests:

- Build and affirm **foundational public health and building science knowledge** related to health in buildings and organizations
- Discuss pertinent public health issues related to WELL features, **underscoring the *why* behind every feature in WELL**
- Showcase the **evidence for solutions** used in WELL drawing on the latest research to ensure you can approach interventions in your project with confidence

FEATURE L01: LIGHT EXPOSURE

OVERVIEW

Part 1: Provide a minimum level of light in all regularly occupied spaces through daylight ingress through interior layout and/or building design or through electric lighting.

SCIENTIFIC BACKGROUND

- Electromagnetic rays between 380 and 750 nm can be sensed by photoreceptors in the eye. This range of the electromagnetic spectrum makes up visible light.[1] All visible light, not just daylight, affects human biology and physiology.
- Illuminance measures is the amount of visible light that reaches a given surface, such as a floor or table. It is measured in lux, or in foot-candles in non-metric systems (1 lux = 1 lumen/m^2, and 1 fc = 1 lumen/ft^2).[1]
- Rod cells are responsible for peripheral vision and vision in dim lighting, while cone cells (of which there are three subtypes: S-, M- and L-cones, corresponding to their respective sensitivity to short, medium and long wavelengths of light) are responsible for daytime and color vision. Further, a class of Photoreceptors called intrinsically photosensitive retinal ganglion cells (ipRGCs) are predominantly responsible for driving non-visual responses to light, including biological processes related to circadian rhythms.
- Light sensitivity varies by cell type.[2] Rod cell sensitivity peaks at 498 nm, M+L cone sensitivity peaks at 555 nm and ipRGC sensitivity peaks at 480 nm.[3,4]
- Just as the pupil acts as the gateway through which light enters the eye and is absorbed by the various photoreceptors on the retina, buildings act as a gateway for the amount and quality of light that reaches the eyes of people inside them. Buildings should deliver an adequate amount of daylight and match the intensity and spectral content of electric lighting to meet people's needs as appropriate throughout the day.

KEY HEALTH AND WELL-BEING EFFECTS

- Alertness and performance are influenced by high-intensity, short-wavelength light (i.e., light with high blue content) such as daylight — which naturally is comprised of wavelengths of light across the entire visible spectrum spanning long-, medium- and short-wavelength light — or blue-enriched electric light (e.g., light that may appear white but is made up of blue, short-wavelength light).[5-9]
- High-intensity, short-wavelength light improves reaction time and subjective alertness compared to dimmer light exposure and has been used to minimize fatigue in patients recovering from a traumatic brain injury or undergoing chemotherapy.[10-17]
- Light has antidepressant properties and can be used therapeutically in clinical settings.[18] Blue or blue-enriched light, including daylight and certain types of electric light, can improve a person's mood.[19-21]
- Light exposure plays an integral role in the regulation of sleep, and bright light exposure can stabilize sleep-wake cycles and improve brain function.[14,22,23] Daytime blue-enriched light exposure has been shown to not only reduce daytime sleepiness but also improve sleep quality at night.[24]
    - Individuals who experience bright light exposure during waking hours (approximately 90 lux) tend to have lower light sensitivity at night compared to individuals exposed to dim conditions during the same time period (less than 3 lux).
    - Brighter light exposure during the day (1000 lux compared to less than 5 lux) can decrease daytime sleepiness and improve neurobehavioral performance.[11]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Delivering daylight directly to interior spaces, or mimicking daylight levels with indoor lighting, allows buildings to be able to deliver light that is optimal for the human body.[25]
- Increasing daytime light exposure or exposure to blue-enriched light in common areas of older adult care homes can have a positive impact on sleep and thus reduce the risk of depression and developing dementia.[26-28]
- Building occupants report more health problems and lower satisfaction the further away they are from a window.[29-32] However, close proximity to windows can lead to thermal comfort and glare dissatisfaction.[31] Some studies suggest that being within view of a window but not directly next to it may maximize satisfaction.[33]

- Hospital rooms with large windows that face the sun for part of the day have been shown to reduce recovery time from severe depression and heart attacks compared to hospital rooms with windows facing buildings or other obstructions.[34,35]
    - Views with more green cover may spur activity in regions of the brain that correspond to positive emotions and motivation, and the attractiveness of the view, as perceived by the viewer, may offset some of the visual discomfort caused by glare.[36,37]
- In spaces where windows or daylight access aren't available, electric lighting may be used to deliver light exposure required during the day.
    - Novel metrics, like melanopic equivalent lux, are being developed for the measurement of light with a specific focus on calculating how photoreceptors in the eyes primarily responsible for circadian rhythms react to light (i.e., the ipRGCs). Traditional metrics are weighted to the response of photoreceptors responsible for facilitating vision (i.e., the rods and cones) and enable the assessment of the impact of light beyond visual acuity, including additional factors such as hormone levels, sleep quality, mood and cognition.[38]
    - Continued research is needed to arrive at a consensus for a standardized, single unit of measurement for non-visual responses to light.

FEATURE L02: VISUAL LIGHTING DESIGN

OVERVIEW

Part 1: Align with a chosen lighting reference design guideline to ensure adequate illuminance is provided in all indoor and outdoor spaces, which considers types of tasks undertaken in the space, the location of the work plane and the ages of people using the space.

SCIENTIFIC BACKGROUND

- The retina is a thin layer in the back of the eye that contains millions of nerves called photoreceptors that are highly sensitive to light. When light enters the eye, two different types of photoreceptors contribute to vision: rod cells and cone cells (three sub-types). These convert rays of light entering the eye into electrical impulses that are then sent to the brain to perceive as and create an image.[39]
- Rods and cones are primarily sensitive to two properties of light: spectrum (i.e., wavelength) and intensity. We perceive different wavelengths of light as different colors on the visible spectrum, and different intensities of light as different levels of brightness.[40]
    - Rod cells show peak sensitivity to light at 498 nm; S (short wavelength) cones show peak sensitivity at 419 nm (appears blue); M (medium wavelength) cones show peak sensitivity at 531 nm (appears violet); and L (long wavelength) cones show peak sensitivity at 558 nm (appears yellow).[41,42]
- Rods are predominantly responsible for peripheral vision. They are also more sensitive to light than cones and therefore are able to facilitate vision in dim conditions (i.e., when luminance or the amount of light coming to the eye from a surface or point is less than 1/100 lux [0.001 cd/m^2] on a surface.[42-44]
    - The sensitivity of rods saturates above about 10 lux [3 cd/m^2], after which point the cones mediate daytime vision. The three sub-types of cones also work in conjunction to facilitate our perception of color.[41,42,45]
- Visibility refers to the ability to detect objects or patterns within some defined distance, as facilitated by the lighting environment. It is influenced by the relationship between four factors: 1) task luminance; 2) background contrast; 3) task size; and 4) observer age and eye function.[46] Therefore, the amount of light required for visibility is largely dependent on the specific context.[46]
- There are many ways to measure light but of particular relevance to this feature is illuminance, which describes the amount of light hitting a surface from a certain distance, which is then reflected to the eye. Illuminance is measured in lux or foot-candles (1 lux = 1 lumen/m^2, and 1 fc = 1 lumen/ft^2).[1]

KEY HEALTH AND WELL-BEING EFFECTS

- Appropriate lighting design can reduce adverse effects like eye strain and visual fatigue, which can help people maintain higher performance at work.[47] This is particularly true for work that relies on good visual acuity, as many computer-based jobs do.[47]
- How much light and the quality of light needed to complete a task varies by specific task and by viewer. Overall, the longer, faster, and more repetitive a task, the more important it is to have enough light. But the measure of "enough" light can vary significantly by person.[48]
- Vision changes with age and people require different conditions and lighting levels to accommodate adequate visual performance as they get older.[46,49,50] These changes typically affect vision around age 40 and do so more sharply starting around age 65. It is still unclear exactly what factors contribute to the decline in visual ability, but studies suggest it may relate to increasing lens density, pupillary miosis (constriction), changes in sensitivity to spatial contrast and a mix of other optical, cortical and retinal changes that occur over time.[51-54]
    - Our eyes also take longer to adapt to differences in light levels as we age: while a slight adaptation phase is normal for any person, changes in the eye that occur with age render it less sensitive to changes in the lighting environment, requiring a longer response time.[55]
- Environments that are either too dim or too bright in terms of illuminance can affect visual acuity, productivity and potentially mood, but reports are mixed on whether effects on mood are merely subjective or correspond to actual differences in objective illuminance levels.[56-59]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Meeting lighting standards appropriate for the task and age of the majority of viewers may not only help improve subjective assessments of whether the lighting environment is appropriate, but also help to improve productivity through improved visual comfort.[60-62]
- Designing lighting environments that are appropriate based on the age of the typical viewer may improve performance.
    - In a field study that measured the light levels at 51 workplaces and assessed legibility performance measured in terms of speed and accuracy using a number of tasks, researchers found that for longer duration tasks, employees over the age of 65 took 6% less time with additional lighting.[63]
- A study was conducted on elementary students assessing oral reading fluency (ORF) - a measure of accuracy and fluency in a language - in groups with dynamic lighting and normal lighting.[64]
    - Dynamic lighting, or focus lighting, consisted of 6000 degrees of Kelvin (K)-100 foot candle (fc) average maintained. Normal lighting consisted of 500 lux with 2500 K.
    - Students who were in the focus lighting group saw a 19% increase in ORF scores by midsemester, compared to students who were in the normal lighting group.[64]

FEATURE L03: CIRCADIAN LIGHTING DESIGN

OVERVIEW

Part 1: Ensure that electric lighting provides an adequate amount of light during the daytime for proper circadian functioning in all spaces and ensure that electric lighting is dimmable in all dwelling units.

SCIENTIFIC BACKGROUND

- Humans function on an approximately 24-hour cycle called circadian rhythms that are synchronized to the time of day by external cues, the strongest of which is light. These rhythms collectively constitute the circadian system, which regulates certain hormone levels and daily variations in alertness, mood and mental and physical performance.[7,22,65,66]
- The circadian system, most powerfully driven by light, controls many aspects of our biochemistry, endocrinology, physiology, metabolism and behavior, including at least an estimated 10% of the human genome.[67,68]
- Intrinsically photosensitive retinal ganglion cells (iPRGCs) are an uncommon subtype of ganglion cells(<5%) that register subconscious and general visual reflexes (i.e. "non-image-forming"), such as daily circadian rhythms and the constriction of pupils.[69] iPRGCs contribute to visual perception as well, as they interpret brightness differentiation and contrast within lighting.[69]
- The receptors in our eyes responsible for circadian rhythms and other non-visual biological processes are sensitive to all forms of light, meaning both daylight and electric light must be considered.
- Lux is a metric based on receptors responsible for vision (i.e., the rods and cones), but new metrics like 'equivalent melanopic lux' and 'melanopic equivalent daylight (D65) illuminance ' are novel because they are based on receptors responsible for circadian and other non-visual processes such as direct effects on mood or learning.[70] These new metrics then measure light a completely different way compared to how lux measures and expresses a given amount of light.
- Further, measuring light at the vertical plane allows a better understanding of the amount of light received at the eye instead of at the work surface (i.e., at the horizontal plane).
- A strong light-dark cycle — both bright days and dark nights — is necessary for a healthy system.[22,70,71]

KEY HEALTH AND WELL-BEING EFFECTS

- Circadian rhythm sleep disorders refer to disorders where internal circadian rhythms aren't aligned with the time for sleep. While there are genetic variables, the environment plays a role in some disorders, which can develop as a function of inappropriate exposure to light (i.e., too little light exposure during the day and/or too much at night).[72]
    - Longer-term, habitually short sleep also is associated with an increased risk of heart disease, diabetes, depression and some cancers.[73-76]
    - There is a high prevalence of cardiovascular disease in shift worker populations, which are full of people who must regularly disrupt their light-dark cycles.[70]
- Light is an acute stimulant, much like coffee, and can directly increase alertness and performance during the day.[77] Some functional magnetic resonance imaging (fMRI) studies also have shown activation of the amygdala in response to light, a brain area that helps to regulate mood.[9]
- Disruption of circadian rhythms has been associated with increased risk of hormone-dependent cancers.[78-80]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- High-intensity light with high content at ~480nm (i.e., daylight or high blue-content light) improves reaction time and subjective alertness when compared to dimmer light exposure.[11-15,81]
- The receptors in the eyes involved with circadian rhythms and non-visual functions work under conditions of longer-duration exposure, but the biological effects of light appear to plateau between 4 to 6.5 hours under conditions of continuous exposure.[16]
- Studies indicate that circadian responses to light are minimally effective below 100 lux and saturate above 1000 lux. Due to the non-linear nature of this relationship, light levels at the lower end of that range can be very effective at triggering circadian or other non-visual responses: 100 lux has been shown to be able to induce 50% of the effect induced by 9100 lux.[82]

ADDITIONAL NOTES

- Any amount of light exposure at night, particularly if that light is high in blue-content (i.e., high content at ~480 nm) may be disruptive to circadian rhythms. But at the extreme, evidence emerging in recent years indicates that chronic exposure to light at night at occupational exposure levels is associated with increased breast cancer rates.[83] Such conditions are common for shift workers, and the International Agency for Research on Cancer designated shift work involving circadian disruption as a probable carcinogen in 2007.[84-86]

FEATURE L04: ELECTRIC LIGHT GLARE CONTROL

OVERVIEW

Part 1: Ensure that luminaires do not introduce glare by meeting requirements on shielding angles or Unified Glare Rating (UGR) values.

SCIENTIFIC BACKGROUND

- Light enters the eye and can become scattered, creating a veil of luminance that reduces the contrast in our vision, thereby reducing visibility. Intraocular scattering specifically can decrease visibility and cause glare.[87,88]
- From an environmental perspective, glare is a product of high ratios in light levels. It can refer to excessive brightness of the light source (whether that is the sun or electric lighting sources) as compared to the area around it or excessive contrast between the darkest and brightest points in a space or on a surface.[89]
- There are strong subjective components to visual comfort, meaning that thresholds can vary by context and person. Tolerance for glare varies by the individual: the same level of light may be considered glaring to one person but not the other.[90,91]
    - Additional parameters should be considered when determining whether something is perceived as glaring. One study found that when comparing two window scenes with the same daylight glare index values, the window with an interesting view was reportedly less glaring than the window with an obstructed view.[92] Similar findings were reported in another study that projected images onto a small screen, wherein the more interesting images resulted in a higher glare tolerance.[93]

KEY HEALTH AND WELL-BEING EFFECTS

- The effects of glare can range from slight visual discomfort, known as discomfort glare, to visual impairment or even injury, known as disability glare.[88,94] People react to glare in a variety of ways – from feeling annoyed to becoming distracted or adopting light-aversive behaviors (e.g., poor posture).[94]
- Managing and reducing glare can alleviate suffering for certain people who experience migraine headaches. The causes of migraines are unclear and vary person to person, but some evidence suggests that certain light exposure exacerbates migraines through mechanisms that may involve the body's circadian rhythms.[95] Glare can trigger migraines, and many people who experience migraines show increased sensitivity to glare and brightness compared to those who do not have migraines.[96-99]
- Mitigating or removing glare also may increase productivity and decrease eyestrain and musculoskeletal pain. Even a moderate amount of glare appears to slow reading and reaction time, and force shifts in posture that can negatively affect visual and physical ergonomics.[100-103]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- The International Commission on Illumination (CIE) provides various UGR recommendations based on different indoor spaces and typical tasks undertaken in those spaces. UGR values appear to correlate closely with subjective ratings of discomfort glare.[104] CIE recommends lower Unified Glare Rating (UGR) values for interior environments to reduce discomfort glare.[105]
    - While UGR can be a valuable tool for quantifying glare in indoor environments, the metric may not be as good of a predictor for glare in conditions of non-uniform luminance as it may overestimate the glare effect.[106-108]
- The experience of glare is essentially a reflection of a ratio comparing glare source luminance, position and size to background luminance.[109,110] Strategies to minimize glare should focus on reducing the luminance or luminous intensity of sources of glare with respect to the field of vision, or otherwise ensure that those sources do not reflect off of vertical or horizontal surfaces, such as shades or shields for luminaires (i.e., the whole lighting unit).[111,112]

ADDITIONAL NOTES

- Younger individuals (under the age of 50) may be more sensitive to glare than older counterparts.[113] This may have to do with age-related effects on vision: individuals may require higher brightness levels to execute tasks as the eyes age.[50,51] However, there is evidence that suggests older individuals take more time to recover (i.e., slower to regain sensitivity for low contrast stimuli) from glare than younger individuals.[114]

FEATURE L05: DAYLIGHT DESIGN STRATEGIES

OVERVIEW

Part 1: Provide at least 70% of occupants with adequate exposure to daylight as defined by visible light transmittance (VLT) for interior layout and façade design in all spaces, and VLT of at least 40% in dwelling units.
Part 2: Provide adaptable solar glare controllable in the form of manual or automated shading devices or through tenant subsidies.

SCIENTIFIC BACKGROUND

- The human eye has a remarkable ability to adapt to a wide range of light intensities. The average office environment might have a mixture of electric light and daylight between 300 to 500 lux, while the noon sun can be as high as 100,000 lux.[115] Lux is the International System of Units (SI) unit of illuminance.
- Humans need light to perform basic visual tasks and regulate their circadian rhythms.
    - Circadian rhythm refers to the approximately 24-hour biological cycle that is synchronized to the time of day by external cues, the strongest of which is light.[65] An individual's circadian rhythm regulates certain hormone levels and daily variations in alertness, mood and mental and physical performance.[7,22,65,66]
- Windows and skylights are important components of buildings that allow daylight to enter a space and connect occupants to the outdoors.
- The use of daylight in buildings represents an important and effective strategy that allows the delivery of high light levels that can supplement electric lighting in an energy-efficient way.[116,117]

KEY HEALTH AND WELL-BEING EFFECTS

- Daylight is an ideal light source for synchronizing the body's circadian system as it provides the exact amount, spectrum, timing and duration of light that is optimal for a variety of biological functions.[118]
- Daylight can impact circadian rhythm cycles, regulate body temperature and release hormones in the body, as well as influence sleep/wake cycles, alertness and mood.[7,22,66,119-122]
    - Many of these effects are also seen through electric light that mimics the qualities of daylight.[5-9]
- The presence of daylight and windows appears to reduce a person's perception of pain, and studies report that it can also reduce medication requests and the length of hospital stays.[123-127]
- Subjective reports show that occupants believe daylight is more beneficial to their health in terms of psychological comfort, visual health and general health. Some occupants believe that electric lighting is harmful to health.[128] Overall, surveys show that most occupants tend to prefer daylight as a light source over electric light.[117,128-130]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Proximity to windows, beyond just having access to daylight, can influence satisfaction with lighting, the overall environment and even overall job satisfaction in some cases.[31] Additionally, building occupants report a greater number of health problems and complaints when situated further from windows.[29-32] However, being too close to windows can lead to thermal comfort and glare dissatisfaction.[31] Therefore, being within view of a window, but not directly next to it, may be optimal positioning for overall indoor environment satisfaction.[33]
    - A study evaluating 20 Danish offices with workstations that were positioned within 7 m [23 ft] of a window found that 70% of respondents were satisfied with the daylighting conditions in the office.[131]
- The size of windows (and the quality of the view they afford) plays an important role in metrics like employee performance at work.[132]
    - One study found that individuals with access to a better view score 25% higher on mental functionality and memory recall tests than individuals without a view. They also found that the absence of a view is strongly associated with increased fatigue.[132]
    - In another study, larger window size was negatively associated with fatigue, headache and eye strain, meaning the larger the view, the fewer symptoms reported by participants.[132]
- Beyond work performance, rooms with large windows that face the sun for part of the day have been associated with reduced recovery time from severe depression in hospitals and after heart attacks, compared to rooms with windows facing buildings or other obstructions.[34,35]

- Window views with more green cover may spur activity in regions of the brain that correspond to positive emotions and motivation, and the attractiveness of the view, as perceived by the viewer, may offset some of the visual discomfort and general dissatisfaction caused by glare.[36,37]
- Window sizes also affect the amount of daylight exposure in a space. One office study found that the optimal proportion preferred by participants was between 15% to 25% of total floor area, and that 40% was the maximum acceptable amount.[133] Another study found that window sizes were reported to be just right (e.g., not too big or too small) when gazing areas were between 20% to 30% of the building façade, regardless of directional orientation (e.g., north-facing vs. south-facing).[131]
- Manual window shading systems are effective but require continuous user attention to manage glare control and thermal regulation.[134]
- Automated window shading systems can balance the need to limit solar glare, while also ensuring that people are exposed to an adequate amount of daylight. People often close blinds and leave them shut, even if the original source of glare no longer exists.[135] It may be beneficial to offer individual lighting control, particularly in offices, as a sense of direct environmental control can positively impact a person's mood and/or behavior.[136]
    - People appear to be more tolerant of glare from daylight than from electric lighting, which may have to do with other benefits associated with proximity to windows.[137-140]

FEATURE L06: DAYLIGHT SIMULATION

OVERVIEW

Part 1: Provide daylight exposure for at least 50% of floor area and validate it through computer simulations.

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    - Circadian rhythm refers to the approximately 24-hour biological cycle that is synchronized to the time of day by external cues, the strongest of which is light.[65] An individual's circadian rhythm regulates certain hormone levels and daily variations in alertness, mood and mental and physical performance.[7,22,65,66]
- The use of daylight in buildings represents an important and effective strategy that allows the delivery of high light levels that can supplement electric lighting in an energy-efficient way.[116,117]

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    - Many of these effects are also seen through electric light that mimics the qualities of daylight.[5-9]
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- Window sizes also affect the area that receives daylight exposure in a space. One office study found that the optimal proportion preferred by participants was between 15% to 25% of total floor area, and that 40% was the maximum acceptable amount.[133] Another study found that window sizes were reported to be just right (e.g., not too big or too small) when gazing areas were between 20% to 30% of the building façade, regardless of directional orientation (e.g., north-facing vs. south-facing).[131]

FEATURE L07: VISUAL BALANCE

OVERVIEW

Part 1: Balance light levels by ensuring that luminance ratios, uniformity ratios and corelated color temperatures (CCT) are kept consistent, or lighting is designed by a professional to account for all preceding considerations.

SCIENTIFIC BACKGROUND

- Brightness is a function of the luminance of a visual target as perceived by our brains. This perception varies depending on how long we are exposed to the light, angle of view and contrast that surrounds the visual target.[141-143]
- Luminance refers to the amount of light entering the eye from a surface or point.[143] It describes the luminous intensity (i.e., the power emitted by a light source in a particular direction, measured in candela) across a given unit of area, measured in candela per square meter (cd/m^2).
- Increasing luminance improves visual performance. However, sometimes it can contribute to visual discomfort and glare.[46,144]
    - There are other factors to consider in regards to luminance, such as the spectrum of light and color temperature.[145] One study notes that viewers are more sensitive to increases in luminance in environments where the color temperature of light is less than 3,000 Kelvin, and that changes under such conditions cause more visual discomfort than in higher color temperature environments.[146]

KEY HEALTH AND WELL-BEING EFFECTS

- High contrast in luminance (the significant difference between the brightest and darkest points in a space or on a surface) can contribute to glare, which is associated with annoyance and distraction, visual discomfort, eye strain, neck and back pain and migraine headaches.[89,94,96-98,100,101]
- People experience a slight phase of adaptation in their vision when transitioning between different lighting environments.[142] In particular, older eyes take longer to adapt to differences in light level and require a longer response time to return to normal visual acuity.[142]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Perceptions of brightness and glare have to do with the contrast between the luminance of a visual target and background, which is why strategies that limit the contrast between the two and maintain uniformity in lighting (i.e., even lighting without significant differences in brightness or darkness within a space) can create a more visually comfortable space and reduce opportunities for glare.[142] One common way to achieve this is by considering luminance ratios, which set a limit on the allowable magnitude of difference between the brightest and darkest point in a room or surface.[143] Luminance ratios appear to correspond well to experienced discomfort. In some cases they may even be better than commonly used glare metrics like UGR in approximating discomfort.[147]
    - The guidelines for luminance ratios are largely derived from best practice recommendations found in lighting design guidelines and standards. It is unclear how much these guidelines are informed by studies investigating health and well-being effects on humans, though they are widely adopted around the world. Further research is needed to elucidate the accuracy of existing recommended ratios and whether there are other considerations to weigh. For example, one study notes that some common luminance ratios to be too stringent in daylit spaces and only useful in electrically lit spaces due to the positive impacts of daylighting.[148]
- Eye fatigue and discomfort due to drastic changes in light levels can be reduced by limiting the magnitude of difference in light levels within and between rooms, or by introducing changes more gradually so the eyes do not have to struggle with an abrupt change in luminance contrast.[111,143,149,150]
- People can tolerate some changes in light levels throughout the day, particularly if they are gradual. But lighting environments that offer relatively stable light levels may be best to avoid causing annoyance, distractions or eye fatigue.[149]

FEATURE L08: ELECTRIC LIGHT QUALITY

OVERVIEW

Part 1: Ensure electric lighting delivers color rendering per regulations and recommended guidelines in all spaces.
Part 2: Manage the flicker of electric lights per regulations and recommended guidelines in all spaces.

SCIENTIFIC BACKGROUND

- Color is a reflection of the portion of the electromagnetic spectrum that is perceivable to the human eye. This means that perceived colors are largely determined by the spectrum of energy emitted by a light source, which can change the way objects appear.
- The color rendering index (CRI) is expressed on a scale from 0-100 that indicates how closely a given light source can portray something's true colors compared to how it would appear under an "ideal" reference light of the same warmth or coolness (i.e., the same correlated color temperature).[151]
- Higher CRI values are considered closer to a reference light that embodies properties of daylight. This measure of how closely a color appears under one light source compared to a reference light source refers to the fidelity of a light source.
- TM-30 refers to a metric that evaluates the color rendition of a light source and is expressed in three properties: color fidelity, color gamut (a measure of saturation compared to the reference light) and color vector graphic (a visual representation of saturation and hue). It also assesses color rendering based on a comparison against 99 color evaluation samples as opposed to the eight used for CRI.[152]
- Light flicker refers to changes in light intensity that occur quickly and repetitively, and the frequency of the flicker determines whether the flicker is visible to the average person. Most people can see flicker up to about 50 hertz (Hz), or 50 cycles per second. The human brain may otherwise continue to respond to higher frequencies of invisible flicker, even as high as 200 Hz.[153,154]

KEY HEALTH AND WELL-BEING EFFECTS

- Humans are typically able to detect very fine differences in color appearance, but our ability to discern these differences depends on the general illumination and the color rendering ability of lamps in the space.[155,156]
- Color preference is an important part of the human visual experience and certain colors can evoke a specific emotional response which varies by individual or culture and affects a person's overall positive or negative impression of a given space.[157-159] Taken together, good color rendition allows environments to be designed to accurately and vibrantly portray the colors of a space.
- When luminance contrast (i.e., the difference in luminance between a brighter area and an adjacent darker area) is low (below 20%), color perception plays a significant role in visual performance overall, making good color rendering particularly important in environments of low luminance contrast.[155]
- Visible flicker is associated with visual discomfort, headaches and eye strain. [154, 160-162] Headaches and eye strain also are associated with invisible flicker.[154]
  - One study found that out of 344 migraine patients, 53% reported that flicker can trigger migraines.[96]
- Exposure to visible flicker for even a few seconds can trigger epileptic seizures in people with photosensitive epilepsy.[162-165]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Higher CRI values allow the colors of a space to be more accurately portrayed and result in greater visual satisfaction. The Illuminating Engineering Society (IES) recommends lamps with a CRI of 80 or higher for general office lighting.[143] IES recommends lamps with a CRI of 90 or higher for environments or tasks that require precise color definition.[143,166]
- Light sources with good color rendering capabilities contribute to a person's comfort level within a space. A reduction in CRI from 100 to 80 could be perceived as less pleasant and many viewers would be able to discern differences in color.[167] A reduction in CRI from 100 to 40 would make a majority of viewers feel uncomfortable and likely report a negative experience.[155]
- While CRI emphasizes fidelity, TM-30 includes a consideration of several other properties that play a role in color rendition and thereby may be more robust and accurate in predicting subjective experiences and perceptions related to color preferences, a sense of the visual "normalness" of the lighting environment and color saturation.[168,169]

- The Institute of Electrical and Electronics Engineers (IEEE) recommends avoiding flicker below 90 Hz based on studies evaluating biological effects of exposure to flicker, such as the onset of headaches and impacts on visual performance.[170]
- If fluorescent lamps are used, care should be taken to ensure they do not malfunction or otherwise flicker below 70 Hz to minimize the risk of seizures.[163-165]

ADDITIONAL NOTES

- Color rendering is particularly important in retail environments, where lighting plays a major role in creating the atmosphere of the space and supporting operations to highlight the color accuracy of products.[171]

FEATURE L09: OCCUPANT LIGHTING CONTROL

OVERVIEW

Part 1: Ambient lighting systems provide adequate lighting zones and systems allow occupant control of light levels, color temperature and color of electric light in all spaces.
Part 2: Visually comfortable supplemental light fixtures that can double the amount of light on a task surface are available upon request at no additional cost to the occupant in all spaces except dwelling units.

SCIENTIFIC BACKGROUND

- The retina is a thin layer in the back of the eye that contains millions of nerve cells that are highly sensitive to light, called photoreceptors. Vision is facilitated by rods and cones, which are photoreceptors found on the back of the retina.[39]
- When light enters the eye, photoreceptors capture the photons of light and turn them into electrochemical signals that project to different parts of the brain and activate image-formation and color perception.[39]
- When light travels through the eye, it is refracted by the cornea and lens to bring images into focus.[39,40]
    - Neural paths are activated when photoreceptor cells absorb a sufficient amount of light. The cells are sensitive to light — specifically the intensity and wavelength of light — because they express a specific photopigment that is activated by absorbing a single photon of light. This is called a cell's unitary response, also known as the "single-photon response".[172,173] A physiological reaction to light that triggers downstream activity in the brain or body depends on whether the sum of each photopigment's contributions passes a certain threshold.
- While it's possible to design a lighting system that supports the visual acuity of the majority of people in a given space, allowing a measure of customizability can further support visual comfort.[174]

KEY HEALTH AND WELL-BEING EFFECTS

- Lighting can trigger headaches and migraines, often depending on the level of brightness (related to glare), pattern or color of lighting among other visual triggers.[175-177]
- The color temperature of light is associated with self-reported changes in fatigue, alertness, daytime sleepiness, sleep quality at night and work performance. Higher color temperatures (i.e., lights with greater blue content) during the day may positively influence these factors.[24,178]
- Both brightness level and light color can impact the mood and tone of a social environment (such as facilitating social interaction or intimate communications).[58,179-181] Allowing for adjustments to these parameters can help create an optimal work space.

HEALTH PROMOTION BENEFITS AND STRATEGIES

- By allowing occupants to self-regulate the lighting systems that surround them, they can reduce glare and adjust light levels depending on their needs.[57]
- However, allowing occupants too much control can potentially create less than ideal lighting situations.[182] Therefore, this suggests that automating systems with manual overrides may be the best way to create productive lighting environments.
- Supplemental or task lighting allows people to control and adjust light levels on an individual basis without significantly altering the overall surroundings and environment. This can improve physical and visual comfort and posture (e.g., slouching to read under conditions of insufficient lighting).[183,184]
    - There has been a shift away from providing supplemental lighting to occupants in an attempt to reduce energy consumption. Ensuring that lamps are energy-efficient can provide individuals with lighting customizability while conserving energy.
- The ability to adjust light levels on an individual basis may be particularly helpful for older adults who require brighter light levels for visual acuity compared to younger counterparts.[56] Therefore, adjustable lighting facilitates age-based adjustments so that viewers can modify conditions to avoid triggering discomfort glare.[113,185]
    - Discomfort glare refers to cases where lighting may not impair vision but is considered too bright (which is often subjective and can vary by individual), causing discomfort and annoyance.

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