Towards a dynamic Daylight Understanding

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Daylighting, Thermal Comfort, Passive Solar Architecture, Daylight Simulation, Metrics

Disciplines
Architecture | Earth Sciences | Environmental Monitoring | The Sun and the Solar System

Comments

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Towards a Dynamic Daylight Understanding

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Abstract

Daylighting is still the most energy efficient lighting strategy, but filtering sunlight might conflict with maximization of solar gains in winter or reducing solar heat gain in summer. In passive solar homes occupants ideally balance visual and thermal comfort. This study explores the relationship of daylight and thermal comfort in a passive solar home using an extended case study method. The resulting daylight measurements reveal a significant tolerance for fluctuations in natural illumination, lower than both high and low thresholds used by emerging dynamic daylight metrics such as IESNA Lighting Handbook, Useful Daylight Illuminance, and CIBSE lighting recommendations. Minimal evidence of electrical lighting use revealed that passive solar occupants have learned to modify the house to receive sufficient daylight while maintaining a comfortable thermal environment. As a result, a preliminary dynamic visual comfort zone is identified, which presents the notion of a metric that includes occupant illumination control.

Keywords: Daylighting, Thermal Comfort, Passive Solar Architecture, Daylight Simulation, Metrics

1. Introduction

Daylighting can easily become one of the most difficult tasks in architectural design. Upon gaining a basic understanding of natural illumination, it becomes clear that a range of ever-changing variables must be accounted for. Additionally, what is considered to be the definition of daylighting and its benefits vary greatly between engineers, designers, and energy consultants (Reinhart et al, 2006 p. 8). The resurgence of dominantly glass facades in recent green constructions would suggest movement towards a more effective balance of daylighting and energy efficiency, but comprehensive energy assessments reveal that popular daylighting strategies are still creating issues of thermal comfort, and therefore affecting both energy efficiency and occupant satisfaction (Konis 2012). Passive solar architecture seeks to design for complete building performance through the consideration of appropriate seasonal treatment of both daylight and solar heat gain.

Historically, when the glass facades of the mid-century became problematic for energy consumption, architects attempted to combat the sun’s negative effects by blocking it from entering buildings entirely. This approach soon proved too antithetical, resulting in sealed spaces with negative effects to occupant health. Studies of occupant responses to daylight in contemporary work environments have revealed a number of psychological, aesthetic, and sustainable benefits provided by the reintroduction of daylight as a design priority (Galasiu et al, 2006). Acknowledgement of the positive influence of daylight...
has placed it as a consideration to architects, but issues of glare and solar heat gain still remain as a hindrance. In addition, the lack of standardization towards natural illumination requirements means that these advantages are not guaranteed in all new constructions. Only those seeking LEED accreditation are subject to the new emerging dynamic daylighting metrics in the US, which aim to insure both quality and performance through the implementation of large datasets and CAD software (Reinhart et al, 2006).

Although new daylighting design software can be an important aid in achieving effective daylighting, the basic schematic design still carries the greatest impact on the success of a effectively daylit space (Tragenza 2011, p. 77). New daylight metrics such as Daylight Autonomy and the Useful Daylight Illuminance promote the notion that daylight is not static, and buildings must be designed with consideration of the natural occurrences (such as climate, surrounding buildings, etc) from the beginning of schematic design. While these factors make up a large component of accessible effective daylighting design, but the operation of the building plays a significant role in the energy performance (Pilkington et al, 2011 p. 4962).

It has been suggested that the effectiveness of current daylight design strategies that meet daylighting metrics still produce uncomfortable interior conditions due to the scarcity of post-occupancy evaluations of daylighting (Konis 2012, p. 344). Various studies have been conducted which evaluate occupant responses to daylighting using a range of existing buildings (Reinhart et al, 2011, Jakubiec et al, 2011, Boyce et al, 2003, Nicol et al, 2006), but many times the buildings in question were initially designed with active mechanical systems in place. This following study examines occupant response to daylighting using a passive solar case study building to evaluate the impact of daylight on occupant satisfaction and thermal performance. By using occupant comfort as a lens for examining the way in which daylight and thermal comfort interact, effective design and operation strategies can be identified for all daylit buildings.

2. Terms

2.1 Daylight Autonomy (DA)- This climate-based metric currently implemented in LEED v4, is “defined as the percentage of occupied times in the year during which minimum, program-specific illuminance levels can be met by daylight alone.” (Reinhart et al 2012, p. 156). Illuminance levels are set in a daylight simulation coputer program, using daylighting recommendation such as the German standard (DIN 3035) or the Illumination Engineering Society of North America (IESNA) Lighting Handbook (Reinhart 2014)

2.2 Continuous Daylight Autonomy- a recently proposed metric that identifies the percentage of illuminance in relation to the Daylight Autonomy upper threshold (Rogers 2006)

2.3 Useful Daylight Index (UDI)- A dynamic daylighting metric defined as “the annual occurrence of illuminances across the work plane where all the illuminances are within the range of 100-2000 lux” (Nabil et al, 2004 p. 41)

2.4 Successful Daylight- This particular study uses thermal comfort conditions in order to identify visual comfort parameters. Therefore, occupant comfort is treated as a composite of visual and thermal comfort, in order to acknowledge the reciprocal nature of illumination and temperature in passive solar design. Daylighting in this paper is defined as “a space primarily lit with natural light and that combines high occupant satisfaction with the visual and thermal environment with low overall energy use for lighting, heating, and cooling (Reinhart et al 2010, p. 4). It is assumed that any successful daylight is achieved through both architectural design and individual occupant adjustment to the illuminated space.
2.5 Daylight Factor (DF)- The most basic and widely used daylighting metric, which gauges sufficient daylight by calculating “the ratio of the illumination indoors to outdoors on an overcast day” (Lechner 2009, p. 390). This metric only provides a rough illumination estimate, due to a lack of consideration for specific outdoor climate conditions.

2.6 Thermal Comfort - Thermal comfort in this study is defined using the Adaptive Thermal Comfort definition of “a comfortable thermal state, or the study of processes and conditions that produce or fail to produce comfortable thermal states” (Nicol 2002, p.164).

3. House Introduction

3.1 Architectural Design

This exploratory research makes use of a single case study passive solar house, which is currently being occupied by two naturalists as an office. Originally built in 2009, the 800 sf house was designed and constructed by an interdisciplinary team of students at Iowa State University for the US Department of Energy Solar Decathlon Competition. A sunspace sits in the center of the floor plan, which provides solar heating for the house in the winter and promotes natural ventilation in the summer using operable glass walls. The sunspace floor acts as a thermal heat sink, and evacuated solar tubes on the roof collect solar energy to provide radiant floor heat. The house is naturally illuminated through a multi-part scheme of dispersed sunspace light, direct southern exposure, and ambient northern windows. Southern light is controlled using exterior louvers as well as interior Roman shades. Northern light is projected into the space through large clerestory windows as well as a combination of a sloped roof and light shelves. Finally, the house floor plan is composed of a series of interlocking spaces that allow for light and air to flow freely throughout, hence the name Interlock House.

3.2 Data Collection

In 2009 the Iowa Department of Natural Resources purchased the Interlock House from Iowa State University to act as an activity center and naturalist office at an Iowa state park. The house was reconstructed with the addition of a data monitoring system comprised of 95 hard-wired sensors, allowing the Iowa State University Center for Building Energy
Research team to study post-occupancy performance. The flow of water, electricity, air, and light are monitored year round by researchers to study correlations between occupancy, design, and performance.

3.3 Context

In 2009 the Iowa Department of Natural Resources purchased the Interlock House from Iowa State University to act as an activity center and naturalist office at an Iowa state park. The house was reconstructed at the park after the Solar Decathlon, with the addition of a data monitoring system comprised of 95 hard-wired sensors. Sensors now allow the Iowa State University Center for Building Energy Research team to study post-occupancy performance. The flow of water, electricity, air, and light are monitored year round by researchers to study correlations between occupancy, design, and performance.

3. Occupancy Introduction

In its current use the Interlock House acts as a naturalist center, where guests to the state park are able to visit for activities geared towards local wildlife education. A varying number of guests circulate through the building during a 4-hour window for 5 days of the week. Three occupants consistently use the building as an office, while 6 turtles and 2 snakes live in enclosures year-round inside the house. Figure 1 further illustrates the post-occupancy inhabitation effect on the basic architectural design.

The 3 permanent occupants of the Interlock House originally brought the quality of daylight to the attention of Iowa State researchers. After roughly a year of working in the house, the electrical lighting had been rarely used during normal office hours. Researchers had been collecting desk surface illumination during this time, which upon closer examination were established to be not meeting pre-design simulation measurements (Leysens et al, 2013, p. 5). This observation prompted the need to develop a research study, including a collection of qualitative occupant feedback so quantitative measurements could be identified and paired with illumination measurements considered to be ‘comfortable’.
3.1 Occupancy Patterns

The original design intended for the building to be used as a residence, where it is assumed that occupants will spend the dominant part of the daylight hours away from the home for 5 days a week. The shift in programmatic requirements has inversed these expectations, making the daylit hours the primary time period occupation. This change in occupancy allowed for a more thorough observation of daylighting, since occupants were able to provide knowledgeable feedback about the daily fluctuations of light quality. The change in program also provided the opportunity for a closer comparison to emerging dynamic daylighting metrics, which either use a percentage of occupied daytime hours to calculate sufficient task lighting (Reinhart et al, 2012, p. 156) or considers the entire range of daylit hours for each day (Nabil et al, 2004).

Although the change in program and occupancy has provided more ideal time period, the nature of the particular occupancy at the Interlock House does not follow a traditional office occupant behavior model used in daylight design simulation programs (Reinhart et al, 2006). Occupants who use the passive house as an office arrive at 8 AM and depart at 4 PM Tuesday-Thursday, while Friday-Saturday the house is occupied from 8 AM to 6 PM.

3.2 Tasks and Activities

In addition to the shift in occupied hours, activities take place in the house that could not have been anticipated by the house designers. Animal enclosures take up a significant part of occupied space and create additional plug loads. The permanent occupants perform office tasks from 8 AM to 11 AM, which resemble office tasks described by office illumination guides but afternoons are comprised of group activities ranging from bird tagging to hikes, to cooking soup. The sunspace is fulfilling one function that was a part of the original house design, with a small garden of herbs and vegetable plants. Further discussion of the significance of specific programmatic behaviors and corresponding illuminances can be found in the Results section of this paper.
5. Methodology

Methodology aims to pair quantitative performance measurements with qualitative feedback from occupants. Figure 3 illustrates the occupant-centric framework used to conduct the study. Both qualitative and quantitative data are examined at four time scales in order to draw connections between the architectural design and effective daylighting performance. A study conducted by Miller, Buys, and Bell (2012) using a similar extended case study methodology serves as a precedent for holistic building evaluation. By conducting interviews with passive solar home occupants and collecting thermal performance data, Miller, Buys, and Bell were able to identify an acceptable level of thermal comfort. This study aims to produce similar results for the performance of natural illumination, in an effort to aid in the development of natural illumination design techniques that improve comprehensive building performance.

Preliminary occupant questionnaire collections have revealed thermal comfort as the primary factor influencing occupant satisfaction. As a result, light and temperature sensors are placed throughout the house to measure building performance, while occupants are allowed to operate the passive house as they would on a typical work-day. Occupants were asked to record any adjustment to the building using an Activity Log worksheet kept in a word processing document. It is assumed that not all adjustments to the house are recorded, and datalogger readings were closely studied to identify any instances of missed activity records.

Occupant questionnaires were collected at the end of the study period for direct comparison to light and temperature measurements. Results of this pairing produced a set of ‘comfortable’ daylight readings that are then compared with dynamic daylighting metrics used by daylight design simulation programs.

5.1 Season

The first stage of this study was conducted over a two-week period during December 2013 and January 2014. This study period allowed for easy comparison to other
daylighting studies using performance information for the winter solstice. The extreme climate conditions in the winter of 2013/2014 make this study especially noteworthy as a result of the extreme polar temperatures experienced. A radiant floor heat system was allowed to run by the occupants as needed due to the anticipated cold temperatures typical to the American Midwest.

The initial stage of this study was determined based on the availability of radiation data collected by on-site dataloggers. Once a methodology was established, a follow-up section of the study was executed using an additional 8 weeks of data collected at the Interlock House from a remote datalogger, without radiation data collected from on-site dataloggers. These 10 weeks of illumination data represent winter-time performances, and data will continue to contribute to the dataset until an entire year is collected.

5.2 Occupant Questionnaire

A longitudinal occupant survey was developed for long-term collection of occupant behavior patterns, expectations, and satisfaction ratings. Beginning in April 2013, the occupant questionnaire was delivered via email once every two months. The survey consists of 6 sections (Table 1) and takes about 5-10 minutes to complete. Survey content was based on the concept of comprehensive building occupation, using a questionnaire precedent by a similar study of passive solar homes by Pilkington, Roach and Perkins (Pilkington et al 2011, p. 4694). The year temperature swings specific to the Midwest and short study period led to the use of only two rounds of occupant survey responses to be used in this study. Public survey cards are currently being collected to further develop comfort ratings at the Interlock House.

5.3 Light Sensor Placement

Three photometric sensors were placed throughout the house to best represent typical activities recorded by occupant activity logs. Activity records showed a strong correlation between required task illumination and eye level height. Using the occupant questionnaire, typical hourly time blocks were assigned to various task locations, revealing that the Bedroom Desk, Kitchen Desk, and Central Hall/Living Room would be locations most representative of the daylight perceived by occupants and visitors to the house.

Kitchen and Bedroom Desk sensors were placed at desk height while the living room was measured using a sensor placed on top a piece of furniture 0.9 meters above desk height. The inverse square law was used to compensate with the height difference, although
it should be noted that these values are relative. This sensor location receives luminance from 4 northern clerestory windows as well as direct light from the sunspace, meaning that the inverse square law is not completely appropriate for accurate illumination values due to the lack of specific point location delivering illumination (Tragenza 2011, p. 39). This study will treat the photometric sensors referred to as Kitchen Desk and Bedroom Desk as accurate, while the values produced by the photometric sensor located in the living room will be referred to as Reptile Cage, and should be read as relative values. Additionally, occupant questionnaires reveal that relative to the bedroom and kitchen, the living room is only found to be 60% effective for tasks performed by the occupants of Interlock House. Further study of this location should be pursued (See Results for further discussion). All illumination measurements are extracted from a spreadsheet produced by an in-house datalogger. See Figure 4 for sensor placement.

5.4 Temperature Datalogger Sensor Placement

Temperature influenced by radiation is measured using temperature dataloggers. Two on-site dataloggers measuring temperature once per minute accompany each photometric sensor location. One datalogger is situated 1 inch above desk height inside a mylar radiation shield. The temperature difference between the protected and unprotected temperature datalogger is then calculated to gauge the amount of heat being produced by solar radiation daily throughout the test period. Temperature dataloggers are accurate within .35 °C (.63°F).

6. Results

Due to the quality-based comments which prompted this study, it was established early on that this investigation would be motivated by an underlying emphasis on factors that could be described as producing quality light. Quality light can be described as lighting perceived as enjoyable through distant outcomes such as context, task, and intentions for the specific lighting condition in question (Boyce, 2013). The nature of the occupant’s work as naturalists is very conducive to changing illuminances, meaning that varying illumination values are not only considered acceptable, but rather ideal. Additionally, the active lifestyles of the occupants lends itself to a more flexible workspace, as well as opportunity for adjustments to architectural illumination controls. Finally, the integration between indoor and outdoor environments characteristic of passive solar designs may increase the occupant’s comfort level with variable or lower illuminances. As a result of these specific conditions of design, climate, and occupancy, an illumination design was achieved that could be described as comfortable.

Representing successful illumination at the Interlock House revealed a disconnect between quantitative and qualitative data. Not only did pre-construction simulation values prove to be an insubstantial indicator of quality, but also to be disconnected from the specific contextual, occupational, and programmatic conditions at the Interlock House. Figure 9 displays further efforts to compare existing task-based metrics as well as emerging dynamic daylighting metrics with Interlock House illumination data. Illumination metrics have been suggested to create indifference towards lighting, because a single quantitative value simply serves to satisfy basic illumination requirements (Boyce, 2013). The variation in illumination data collected at the Interlock House begins to delineate a range of illuminances that could not only produce a more enjoyable space, but also add to the refinement in approach towards illumination design guided by metrics.

There is a great deal of anecdotal evidence that occupants prefer daylight in workspaces (Galasiu et al, 2006), and field studies have revealed a significant degree of adaptability held by office workers towards illumination intensity (Nicol et al, 2006). But occupants do not just tolerate the fluctuations in daylight performance, they actually rely on a perceivable
level of illumination variance (Tragenza 2011, p. 5). This case study set out to identify if this preference for daylight is affected by the solar gain essential for effective passive solar performance, and concludes that through strategic architectural design specifically intended for independent daylight performance, occupants are able to achieve a ‘comfortable’ illumination level without the need for regular electrical lighting.

As a result of the dominantly independent daylight performance, recorded illumination measurements were used to place quantitative values on time periods characterized by tasks that occupants found to be comfortably illuminated. The product of this quantification process is a preliminary dynamic visual comfort zone, which is used to compare illumination performance against emerging dynamic daylight metrics. The dynamic visual comfort zone identifies both ‘comfortable high values’ as well as ‘comfortable lows’ for time periods determined from occupant work schedules (Figure 9).

Daylight Autonomy (DA)(Reinhart et al, 2006) set at 500 lux was found to be too high in relation the dynamic visual comfort zone low threshold, suggesting that Continuous Daylight Autonomy (Rogers 2006) may be more effective towards the evaluation of effective daylight design during the initial building design phases. The Useful Daylight Illuminance (UDI) (Nabil et al, 2004) low threshold of 100 lux was found to be acceptable against the preliminary dynamic visual comfort zone low threshold, while the UDI upper limit was much greater than any illumination value recorded during the test period at the Interlock House.
Details of Daylight Tolerance

Self reported occupant activity logs showed minimal evidence of electrical lighting usage, meaning that little data was collected about specific instances in which the occupants found the house to be visually uncomfortable. This is considered to be an indication of a successful daylight design, as occupants do not feel an overwhelming need to revert to electrical light. Datalogger illumination measures support the sparse electrical light usage from activity logs, through the strong correlation between interior and exterior daylight fluctuations. Figure 6 shows a remarkable correlation between outdoor light and indoor daylight recorded on January 8, indicating that daylight successfully illuminated the space very minimal intervention from occupants.

Similarly, Figure 7 demonstrates the influence of sunny outdoor conditions on the indoor illumination on December 28. The bedroom desk is located roughly 2.5 meters from the south façade, and faces north against a wall. As a result, the occupant is able to work while the sunspace and clerestories light the bedroom desk. The bedroom location rarely needs any kind of illuminance intervention, which can be seen in Figure 7 through the curvature of illuminations levels, showing a strong resemblance to the exterior illumination level. Alternatively, the kitchen desk on December 28 demonstrates a need for illumination modulation without the use of electrical light. The kitchen desk currently faces the southern kitchen window, which creates a need for control of glare and privacy. Figure 7 shows the kitchen desk illumination measurements to maintain around 550 lux, as a result of shading device use, while illumination in this location still varies as light from the adjacent sunspace periodically enters the kitchen. Finally, the electrical lights are turned on from 17:00-18:30, well after sun had set, indicating that occupants truly need the light fixtures on this day only after dusk.

The illumination measurements taken on December 28 demonstrate a pattern of influence from “killer variables” (Boyce et al 2003, p. 35). These are variables that have been identified in workplaces to have significant influence on productivity (Boyce et al 2003, p. 35). The ability to individually control a space has a large impact on office worker satisfaction and productivity (Boyce et al 2003, p. 36). Use of window shades at the kitchen desk displays an adjustment of the personal control “killer” variable, through the lack of electrical lighting use. Another “killer variable” to workplace productivity is building depth created by floor plates that are too deep (Boyce et al 2003, p. 35). The bedroom desk demonstrates an ideal scenario for desk orientation working in combination with building depth. The occupant’s back faces towards the main southern daylight source, blocking direct light and potential computer screen glare. Meanwhile, northern clerestory windows and adjacent light shelves project ambient light down into the space, allowing for a reasonable and continent level of daylight to assist with office tasks.
The lack of illumination consistency for all illumination sensor locations throughout this study period displays the tolerance occupants hold for daylight fluctuations. It is clear that occupants have found strategies to work in the daylight conditions provided by the Iowa climate, and modulated by the illumination design at the Interlock House. This acceptance of illumination design and adaption using shading devices is exactly what prompted the investigation into qualitative factors influencing quantitative measures that did not measure up to the 500 lux (50 fc) prompt used for the original Solar Decathlon design competition (Leysens et al 2013, p. 5). Rather than the architectural design, the 500 lux metric was determined to be the unreliable variable causing the illumination performance to not align with pre-construction computer simulations.

6.5 Effective Architectural Design

Identifying the positive effect of the “killer variables” calls for an evaluation of architectural design strategies that produced success in daylight design at the Interlock House. The original architectural design prompt called for an 800 square foot (243 sq. m) home entirely powered by solar energy. The decision to execute this plan using passive solar technology meant the architects were able to achieve a high level energy efficiency and daylight performance that would have not been otherwise possible with an active mechanical system. The Interlock House now regularly teaches its occupants, guests, researchers, and original designers how a passive house needs an active user. In order to stay comfortable in the Midwestern United States climate, occupants must be aware of how to let the sun heat their home in the winter, and promote maximum air flow during hot, humid summers.

Walls were placed at sloping angles adjacent to windows sized for multilayered illuminance, resulting in the autonomous daylight performance currently in place today. Figure 2 shows how direct southern light is able to enter directly into the kitchen and bedroom, but a combination of interior and exterior shading devices provides occupants the opportunity to adjust illumination and/or solar gain. If direct southern light is found to be too great or intense, the Interlock House is able to still maintain daylit illumination while southern windows are completely covered. This is achieved through ambient northern light bounced downwards between sloped roof and light shelf planes, as well as through the sunspace, which emits large amounts of light and radiation through glazed southern and roof planes.
The multi-layered daylight scheme is precisely what has allowed occupants to independently control their preferred illuminance level. For example, due to spatial limitations the kitchen desk is positioned towards the southern facing window. As a result, the shades are closed at this sensor location, but Figure 7 illustrates the more constant, but still changing illuminance received at this location from the adjacent sunspace and light shelves.

### 6.2 Radiation Measurements

Each light sensor location was accompanied by a pair of temperature dataloggers, which together were used to measure the solar radiation of that location. Figure 8 illustrates that temperature dataloggers outside Mylar radiation shields regularly collected temperature measurements that are ~.8°C higher than those protected from radiation. Although a slight correlation between mean radiant temperature and sensible air temperature can be detected, the temperature measurement between the two dataloggers maintains the same difference throughout the entire day. Occupant questionnaire responses support the suggestion that Figure 8 displays that solar radiation does not greatly impact the interior conditions of the Interlock House at the measurement locations. But the consistency of temperature maintained at ~1.6°C indicates a stronger need for continued evaluation of the impact of solar radiation at the Interlock House.

### 6.3 Dynamic Visual Comfort

The necessity for active building operation in a passive solar home is exactly what has allowed for the emergence of a dynamic visual comfort zone. Occupants must collaborate with the architecture, tuning to its behavior to make themselves comfortable. While the dramatic Iowa climate has created an occupancy characterized by thermal comfort challenges, passive solar performance creates an inextricable link between thermal comfort and daylight performance. When adjusting their thermal environment, occupants modulate the daylit environment as well. The resulting daylighting records reveal a level of illumination tolerance that begins to factor in heat caused from solar gain, privacy, view,
energy efficiency, along with many other factors that are very familiar to any house dweller, but sometimes difficult to address as an architect.

The natural fluctuations in daylight performance meant no one specific hour, day, or minute could be used as representative of typical illumination at the Interlock House. Historically, the Daylight Factor has been used to calculate a general illumination reading, but the growing prevalence and availability of simulation software has created a higher demand for reliable and accurate illumination data, to provide architects with climatically and temporally informed illumination predictions. Taking this recent priority shift in mind, it was established that in order to represent illumination performance at the Interlock House, a range of values must be identified. These values would be derived by not only the architectural design, but also the occupant preference for control and the type of task being performed. Architects are acquainted with the idea of specifying task illuminance requirements while designing interior spaces (Grondzik et al 2011, p. 681), and shading devices are also common elements in contemporary facade design. A less common practice though, is to design with consideration of the occupant’s autonomous ability to adjust themselves (i.e. moving from one side of a table to another) (Jakubiec 2011, p. 167), their environment (Reinhart, 2004), or the task.

At the Interlock House, occupants must actively operate the passive solar home, meaning that they have adjusted to a lifestyle that asks for their participation in the building’s ability to function. By prompting occupant’s to rate their satisfaction with illumination, they are asked to respond to an illuminated environment after they have made their best effort to accommodate it to meet their needs (regardless of the environmental, financial, or social motivations for making those accommodations). As a result, the preliminary dynamic visual comfort zone is based on illuminance values that are informed by both the architecture and the occupant who operates that building.
Considering the occupant-centricity of this preliminary metric, the occupant questionnaire feedback was used to inform the means by which the dynamic visual comfort zone was identified from the large datasets available at the Interlock house. Table 1 describes how the Occupant Questionnaire was delivered every two months, and the ‘General Building Performance’ section asked for a rating of how many days each month specific issues were found to be uncomfortable at certain times of the day. Illumination discomfort could be indicated through both glare and under-illumination questionnaire prompts. While filling out this section of the survey, it is likely occupants retroactively thought about how many days they found illumination (does not differentiate between daylight and electrical) uncomfortable. Occupants unanimously rated the illumination to be uncomfortable for ~25% of the month during this study period, meaning that upon reflecting on that month they were rating specific time instances rather than specific time periods. Additionally, this qualitative information represented a 2-week period, while the quantitative illumination measurements were only available on a minute-by-minute basis.

In order to most accurately pair these two time frames, illumination measurements for each minute were divided into daily bins for further analysis. Daily bins allowed illuminance values to be organized by daily climate conditions and occupant activity that would have affected data for each day. Climate based metrics have become increasingly prevalent in dynamic daylight simulation programs (Reinhart et al, 2006), so special attention was given to insuring the daily impact of climate on illumination data collection was retained.

The CIBSE Code for Interior Lighting recommends a range of illuminance levels which are appropriate for a series of specific tasks. This notion of task-based illuminance was used as the next step in the process of determining a dynamic visual comfort zone. Using a typical work schedule provided by occupants, daily illumination measurements were divided into 3 bins; the morning (8 AM to 11 AM), Lunch Hour (11 AM - 1 PM), and afternoon (1 PM - 5 PM). Work as a naturalist asks for a substantial range of skills and

Figure 12. January, February, and Study Period high illuminance records
activities throughout the day, ranging from computer work to plant care (the right hand column of Figure 9 further describes typical tasks and time blocks), so it was necessary to divide these time periods based on illuminance needed to accomplish a range of tasks. Each time bin was then at a similar time increment to the comfort rating recorded in the occupant questionnaire. The unanimous 25% uncomfortable illumination rating was then used to remove the lowest bin of illumination data during each time period. Figure 9 further illustrates this process. After daily bins were sorted, linear regression trend lines were used to identify values that could be used as representative illumination data for that time period. Figure 10 shows the variation of illuminance data collected during each daily time bin, and the linear regression values.

7. Conclusion

It is important to acknowledge, that this illumination scenario is made possible by the passive solar nature of the case study solar home. Occupant adjustment to the architecture is informed by the need to learn strategies for balancing solar gain and natural illumination, meaning that occupant behavior is aligned with the design intentions of the passive solar home. A tolerance of fluctuating daylight is accomplished because occupants have actively worked with the house design to achieve comfortable and efficient performance. The aforementioned “killer variables” have allowed occupants to avoid radiation through shading or desk orientation, meaning that radiation does not play a large role in illumination levels perceived as comfortable by occupants. Further examination of the role of radiation at the Interlock House should be pursued, but the illumination tolerance measured in this preliminary study may suggest that Dynamic Visual Comfort Values could be applicable to buildings with active mechanical systems as well, provided that similar opportunities for occupant control and daylight availability are present.
Adjusting metrics to compensate for a lower range of tolerable illuminances presents great opportunity for improved energy efficiency and occupant satisfaction. In the United States, space heating makes up 45% of residential energy consumption, while lighting makes up 6% (US DOE, 2014). While many contemporary building are using strategies and emerging daylight simulation programs to lower lighting consumption, space heating can easily become compromised. Taking a passive solar design approach promotes the notion of designing for a balanced treatment of illumination and thermal comfort that could produce a more comprehensive design and energy performance. Daylight metrics provide an opportunity for introducing a multi-faceted and energy efficient approach to daylight design. This has begun to happen through the recent accomplishments in climate-based metrics, as well as a growing knowledge based of post-occupancy illumination values.

8. Appendix

This study was developed as a pilot study, used to explore a methodology designed to pair an abundance of quantitative illumination data with reliable occupant survey data. The Results section of this paper describes a preliminary set of dynamic visual comfort values supporting a satisfactory work environment performing below it’s intended level. The initial two-week period was established based on the availability of on-site radiation data. When radiation measurements provided inconclusive information, a follow-up stage of the study was performed using an expanded dataset. Minute-by-minute illumination values were evaluated for the months of January and February 2013 to further explore the feasibility of an occupant-based metric. While this information substantiates the dynamic visual comfort zone discussed in Section 6 of this study, statistical conclusions cannot be made at this point. Nonetheless, the Figure 12 and 13 clearly demonstrate the influence of sensor location within the house, killer variables, and monthly variations. Future research will seek to collect and interpret an entire year of illumination data, evaluating both killer variables and seasonal changes at the Interlock House, in an effort to continue identifying a dynamic visual comfort zone.

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