Between research and practice: a comparative analysis of daylight design predictions in atriums

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ABSTRACT: Internal, multi-story atria present an opportunity to harvest daylight as well as create connections to the outdoors in commercial and educational buildings. They also have the potential to help moderate well-being for occupants and provide informal gathering spaces that form social interactions for buildings' users. Despite the increased deployment of atria in contemporary, sustainable buildings, there is a lack of studies investigating the relationship between atrium design strategies, expected outcomes, and their realized impacts on occupants' comfort, health, and experience. The intent of this paper is to investigate the effectiveness of two different atria typologies in two LEED campus buildings from both building performance and occupants' perspectives. A comparative field study was conducted in these two buildings to assess how the shape, form, orientation, and geometry of the two atria impacted daylighting autonomy, glare, chronobiological light response, occupants' perceptions, and functional use of both spaces.

This paper concludes with insights on the relationship between daylighting design metrics employed in practice and their consequential impacts on the real space as perceived by the occupants. It attempts to answer whether an atrium that meets building performance standards necessarily translate to a healthy indoor environment and positive human experience. Results from this study suggest that atrium design can be optimized to balance daylight quantity and quality through prescribed design parameters. However, the success of the design with the intent of a space that encourages social interaction requires more attention to human behavior, atrium function, and typology.

KEYWORDS: Daylight, Metrics, Post Occupancy Evaluation, Health

INTRODUCTION

To achieve sustainable design strategies in green buildings, designers are becoming increasingly interested in employing effective daylighting design in their buildings. Introducing daylight into a building's deep core can offset electric lighting loads. This is usually achieved with employing different atrium designs. An atrium can be defined as a multi-storied covered light well in a building, usually with a skylight. These specific atrium typologies have gained popularity because they not only allow daylight to reach core areas that cannot be reached by generic side lighting strategies, but they also create a social center and an intermediate state between inside and outside spaces in buildings.

Building science researchers have extensively measured daylight parameters with regards to meeting instrumental energy efficiency and visual comfort benchmarks. Though these buildings may excel in performance as per benchmark requirements, how does this translate to an overall success of the atrium design? These atriums are intended to create spaces for social interaction. If occupants are to spend extensive periods of time in these spaces, shouldn't there be more assessments of the spaces with regards to occupant well-being rather than just instrumental metrics that fulfill other requirements in sustainable designs? This paper compares and contrasts the performance of two atrium types in LEED certified buildings pertaining to both the instrumental building performance parameters and those parameters concerning occupant well-being. It aims to highlight the difference and importance of addressing both aspects when designing atriums.

1.0. ATRIUM DESIGN

1.1. Atrium allometry

An atrium, open air or skylight covered, is a product of modifying many variables. Parametric studies have investigated the effects of modifying its shape, form, orientation, and geometry. Buildings, regardless of their typology, tend to be oriented parallel or perpendicular to streets. Older cities had no grid patterns or planned street systems. This resulted in a large variety of atrium orientations due to organic growth and unplanned development. New, planned and systematic cities comprise of streets that followed cardinal points (North - South, East - West). Thus, atriums started to follow those axis with an occasional 45° tilt off the cardinal points for a more evenly distributed amount of sunlight on all facades when desired (Reynolds 2002).Decisions regarding which orientation is optimum should be based on which functions are zoned on the long and short sides of the building. The assessment should also consider which aspect is more problematic: winter heating or summer cooling. Spaces are then allocated more precisely within buildings with respect to seasonally and hourly changes according to the effect of solar radiation (Moradchelleh 2011)

Quadrilateral atriums can be elongated in different directions. Plans elongated North-South have longer walls facing East and West. These receive direct sun across the length of the courtyards around noon but can be partially shaded by the long walls during the earliest and latest hours of the day. This is typically ideal in hot and dry climates where courtyards are commonly oriented between Northeast-Southwest and North-South. Atriums have been used in buildings in a variety of geometries and may also take on the form of non-quadrilateral shapes: pentagonal, hexagonal, heptagonal, octagonal and even irregular cases. These have an adverse effect on shading. Parametric studies have analyzed the effect of increasing the number of sides of atrium wall enclosures and the results indicate that the percentage of shaded areas decreases with the increase of number of walls in the geometry (Muhaisen and Gadi 2006).

The height to width proportions of an atrium's enclosure play a role in regulating the microclimate within a building. Simulations investigating ambient air temperature changes in atriums indicate that with the increase in height of wall enclosure, temperature decreases significantly by as much as 30°C. This is due to the fact that direct solar radiation is blocked during specific hours of the day (9:00 to 18:00), resulting in larger shaded areas which are critical to prevent overheating in hot climates. However, when the sun is directly above the atrium, with a low solar zenith angle (12:00 to 15:00), thermal conditions may be uncomfortable. Higher walls reduce the sky view factor within the courtyard and compromise illumination levels. A balance should be optimized between thermal comfort and illumination levels whilst considering human subjective assessments and objective measurements since occupants may be more tolerant to some thermal conditions due to psychological adaptation.

On the other hand, it has been noted that atriums with low surrounding walls worsen the condition indoors than outdoor areas in hot climates. This can be explained with simulations that show that low walls do not block the sun at all, so there is no shading. Furthermore, though these low enclosure walls may not block sun, but they do in fact block wind in exposed atriums and so reduced wind speed minimizes comfort. Ideally, cold climates would decrease the height to one level (1:6). Temperate, hot and dry climates would increase the height to two levels (2:1). Hot and humid climates tend to increase the height to three levels (3:1) by following the imperative that the use of deep courtyard forms are beneficial for hot climates and shallow courtyards work best in cold climates (Ghaffarianhoseini, Berardi, and Ghaffarianhoseini 2015)..

1.2. Occupant behavior and spatial analyses

Architecture plays a major influential role in how much light exposure a building occupant receives and how an occupant might behave inside buildings, respectively. On a large exterior scale, light penetrating a building's interior can be predetermined based on the surrounding environment's exterior geometry. This can be mediated with the building's orientation and façade design by altering window parameters: ratio, size, position, glazing type and whether shading devices will be allocated. On a smaller interior scale, light penetrating the building's envelope is either enhanced or diminished based on the indoor profile, surface properties and interior reflectance. Designers can also modify indoor light exposure through the use of electric lighting. They specify the lamp type, spectral properties and position. Occupants have the freedom to distance themselves from certain light sources and based on the degree of control they have on indoor lighting controls.

Access to daylighting in a building can impact human behavior in spaces. Many of the methods of spatial analysis and indoor space modeling explore the dichotomy between the social (human occupants) and physical (building fabric and structure) parameters of human occupancy and use of space. They investigate the general patterns of usage including movement and flow within a building, as well as physical analyses to improve usability of a building (Worboys 2011). The concept of the depth of building zones should not be simply interpreted as the accessibility of a space but more fundamentally, its connectivity. This is especially important when assessing an occupant's exposure to available daylight, for the space-to-space permeability and the relation of visibility which passes through connected spaces. This can be assessed using computer simulation methods where the resulting axial lines in an axial map can be regarded as the fewest number of visual paths in the existing space where each intersection plays as a turn of sight, which becomes a depth (Kim et al. 2008). The spatial and functional differences between spaces that we find through the analysis of permeability in the building also appear in the analysis of visibility. Two of the measures Benedikt (1979) focused on in particular were the *area of the isovist* which describes the total amount of area visible from a point and the *perimeter length of the isovist boundary* which describes how quickly the view changes as you leave the point. These measures quantify different aspects of how a person may experience the space, and together give a fuller description of their exposure to daylight. This highlights the importance of investigating vertical illuminance at different orientations to better understand the daylight potential of a space.

1.3. Daylight performance metrics and occupant well-being parameters

As previously discussed, various atrium configurations impact daylight availability within buildings. This can be measured with instrumental daylight metrics, as often used by the design industry, to assess the building's performance. The most familiar and widely used photometric unit of measure for light is photopic lux. It quantifies illuminance, the total power of light falling on a detector surface from any direction as perceived by a standard human observer (Serra 1998). What primarily started as a means to assess the daylight conditions needed to provide minimally adequate daylight levels in Europe resulted in the development of one of the earliest metrics for daylight performance. The Daylight Factor (DF) is the ratio of internal illuminance at a point in a building to the unshaded, unobstructed, external horizontal illuminance under standard CIE overcast sky conditions - expressed as a percentage (Moon 1942). An average DF of 2% across a given space is usually required for it to be considered sufficiently daylit. This metric, which was not developed with the intention to accurately assess daylight performance, does not account for different sky conditions and is not sensitive to building orientation, geographic location, or sun position. To address the shortcomings of this overly simplified metric, more complex hourly daylight metrics were developed and adopted.
Daylight Autonomy (DA), first defined by Reinhart (2004), is the percentage of occupied times of the year when a minimum work plane illuminance threshold of 500 lux can be maintained by daylight alone. It uses work plane illuminance as an indicator of whether there is sufficient daylight in a space so that an occupant can work by daylight alone. This metric is somewhat problematic as it proposes binary thresholds which might unjustly differentiate spaces based on measurements of light changes that may not be perceived by the human visual system. This was further developed and standardized to what is known as Spatial Daylight Autonomy (sDA) which is a percentage of an analysis area that meets a minimum horizontal daylight illuminance level for a specified fraction of the operating hours of the year (Heschong et al. 2012). A commonly used benchmark is to achieve 300 lux for 50% of the time.

Since the common measurement of illuminance, photopic lux V(λ), describes the spectral sensitivity of one aspect of human cone-based vision, these photopic units have limited utility. The spectral sensitivities of the visual and non-visual systems (555 nm and 490 nm, respectively) are different. Thus, illuminance based photopic lux metrics are not appropriate to evaluate non-visual responses. Researchers and professionals in the field have resorted to developing a set of metrics, simulation, field study methods and technological tools for new daylight health effective modes of measurements.

The biological effects of light on humans are usually translated from spectral power distributions and measured in equivalent melanopic lux(EML), a proposed alternate flux density metric that is weighted to the *intrinsically photosensitive retinal ganglion cells* (i*pRGCs)* luminous efficiency function, which peaks at 490 nanometers and is based on the action spectrum of melanopsin - instead of the cones' photopic luminous efficiency function V(λ), which peaks at 555 nanometers and is based on the response of foveal, long and middle-wavelength sensitive cones, which is the case with traditional lux (Enezi et al. 2011). This translation is used to understand how much the spectrum of a light source stimulates ipRGCs and affects the circadian system.

The equivalent melanopic lux metric has been adopted by the WELL Building Standard (Institute 2017) which was launched in October 2014 by The International WELL Building Institute. This standard is commendable as it not only assesses the design and operations of buildings much like the predominant rating systems, but it, more importantly, looks at how they impact and influence human behaviors related to health and well-being. The light category in the WELL standard aims to "minimize disruption to the body's circadian system, enhance productivity, support good sleep quality and provide appropriate visual acuity". For work areas, they should meet at least one of two requirements: (1) At 75% or more of workstations, at least 200 equivalent melanopic lux is present for at least the hours between 9:00 AM and 1:00 PM for every day of the year. (2) For all workstations, electric lights provide maintained illuminance on the vertical plane of 150 equivalent melanopic lux or greater. In living environments such as bedrooms, bathrooms, and rooms with windows, one or more fixtures should provide 200 or more equivalent melanopic lux. Lights in workplace breakrooms are required to maintain an average of at least 250 equivalent melanopic lux. They may be dimmed in the presence of daylight but should be able to independently achieve these levels. Learning environments need to meet at least one of two requirements: (1) At least 125 equivalent melanopic lux is present at 75% or more of desks, for at least 4 hours per day for every day of the year. (2) Ambient lights provide maintained illuminance on the vertical plane of equivalent melanopic lux greater than or equal to the lux recommendations in the Vertical (Ev) Targets of the American National Standards Institute and Illuminating Engineering Society IES-ANSI RP-3-13.

The Lighting Research Center at Rensselaer Polytechnic Institute has also proposed a metric, known as "the circadian stimulus" for applying circadian light in the built environment (Mariana Figueiro 2017). It uses irradiance weighted by the spectral sensitivity of every retinal phototransduction mechanism that stimulates the biological clock, as measured by nocturnal melatonin suppression. The metric is derived from a transformation of circadian light into relative units, from 0 to the response saturation of 0.7, and is directly proportional to nocturnal melatonin suppression after one hour of light exposure (0 to 70%). The recommended levels aim for a circadian stimulus greater than 0.3 during the day and less than 0.1 in the evening. A circadian stimulus calculator is also made available online for lighting professionals to enable them to convert the photopic illuminance at the eye provided by any light source and level, into the effectiveness of that light for stimulating the human circadian system (Rea and Figueiro 2016, Rea et al. 2010).

2.0. FIELD STUDY SETTINGS

The aim of this study is to compare the daylighting performance of two different atria geometries inside two educational buildings of similar size and spatial typologies yet different atria geometries. Both buildings excel in sustainable design strategies employed, green technologies and have accomplished LEED certifications. The two buildings selected for this study are: The Lewis Integrative Science Building (LISB) which has achieved LEED Platinum certification and Lillis Business Complex which has achieved LEED Silver certification. Both buildings are located at the University of Oregon Campus, Eugene, Oregon. They both claim to incorporate atriums to enhance daylight availability and encourage social interaction. This study assesses how these two different atria typologies but with similar goals perform differently in terms of daylight availability for visual task needs and occupant well-being.

Figure 1. Interior shot of the East-West oriented rectangular atrium in Lewis Integrative Science Building (Author, 2019)

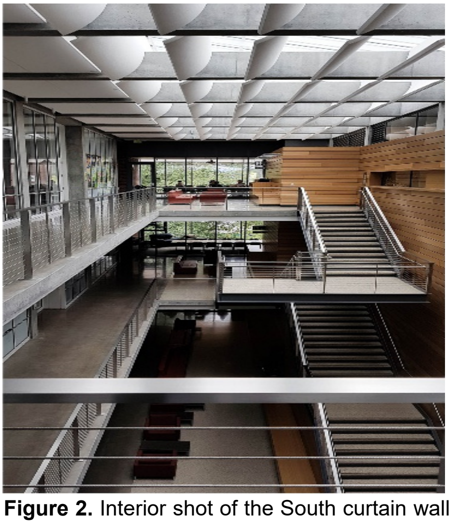

Figure 2. Interior shot of the South curtain wall and central atrium in Lillis Business Complex (Author, 2019)

The Lewis Integrative Science Building (LISB), opened in 2012, is home to research oriented to human brain, molecular biology, nanotechnology and solar energy. The building, with an area of 107,000 gross square feet, consists of four occupied stories, a subterranean level and a fifth floor which contains mechanical equipment. It is comprised of faculty offices as well as office space for graduate and post-doctoral students, collaboration and meeting spaces and more than 30,000 square feet of wet labs, dry labs, an MRI facility, ERPS booths and other instrument labs. It was designed by HDR Inc. and THA Architects with the design intent to achieve LEED Platinum certification by incorporating energy savings including solar shading, daylight harvesting, night flush cooling, immense solar panels, and heat from an adjacent utility tunnel. The research facility uses about 58 percent less energy than conventionally designed buildings of similar size and function. The primary component of interest in this building is the four-story, rectangular atrium elongated in an East-West orientation. This serves as the heart of the building for circulation, to encourage interaction between scientists from different disciplines and allows daylight to penetrate the building from within.

Lillis Business Complex, opened in 2003, houses the University of Oregon's College of Business. The building, with an area of 196,500 gross square feet, consists of four occupied stories comprised of classrooms, lecture halls, computer labs, conference rooms and offices. It was designed by SRG Partnership with the design intent to achieve LEED Silver certification and incorporates one of the largest solar installations in the Northwest and one of the pioneering uses of photovoltaic solar glass in the world. The building design and configuration helps it achieve maximum energy efficiency, exceeding state energy code requirements by more than 40 percent. Much like LISB's atrium the atrium in Lillis Business Complex is the heart of social interaction, circulation and daylight penetration. However, rather than being elongated, this typology is more central with flanking zones.

The study was conducted on a typical morning and afternoon day of ASHRAE climate zone 4C, characterized with overcast sky conditions. Illuminance levels and spectral power distribution measurements were taken at several points within the atriums on both the horizontal plane and vertical plane at the North, East, West and South cardinal points. HDRI photographs were also taken to further analyze the space throughout the full day. The results from this luminous environmental analysis were interpreted by computing visual comfort and chronobiological light metrics. Metrics computed included: Daylight Factor (DF), Daylighting Autonomy (DA300), Annual Solar Exposure (ASE), Daylighting Glare Probability (DGP), Circadian Stimulus (CS) and Equivalent Melanopic Lux (EML).

3.0. RESULTS

Findings related to both atria performance are broken down into three analyses: daylight factor and illuminance levels, circadian stimulus, and equivalent melanopic lux metrics. Each location point reports the measurements for both the horizontal plane and vertical plan at at the North, East, West and South cardinal points for the morning (9-11am) and afternoon (1-3pm) hours. In the tables, cells that are shaded in gray indicate that measurement did not meet the benchmarks. The daylight factor benchmark was set at 2%, illuminance levels at 300 lux, circadian stimulus at 0.3 and equivalent melanopic lux at 250 EML.

Illuminance levels measurements taken on the horizontal plane tend to be greater than those in the vertical plane facing different directions. This misconception can be misleading to designers as they make assumptions that meeting the 300 lux benchmark for the horizontal plane is sufficient. Some tasks require occupants to look in different vertical directions, this requires designers to different views and planes into consideration. It is also noted that meeting the 300 lux benchmark is not a strong indicator of maintaining the 0.3 circadian stimulus or the 250 EML benchmarks. Both circadian stimulus and equivalent melanopic lux biological benchmarks appear to be more difficult to meet than the visual task illuminance level benchmark requirements. In some cases, the space requirements may require more or less illuminance levels. Designers should anticipate how these changes will be reflected in creating biologically bright or dark spaces.

The elongated atrium in the Lewis Integrative Science Building performed poorly on the lower levels, especially during the morning hours. This critical observation hinders the atrium's performance since the circadian stimulus benchmarks are not met during the morning hours, when it is most vital. The central atrium in Lillis Business Complex meets the benchmarks at most points during both the morning and afternoon hours. This is due to the South curtain wall which allows more daylight to penetrate the building through side lighting techniques. This is observed in the South vertical plane measurements. Though it aids in increasing daylight, it also increases discomfort glare.

CONCLUSION

This paper has investigated the performance of two different atria typologies from both visual requirements and biological circadian potential standpoints. From the results it can be concluded that daylighting measurements and metrics are multi-faceted and might not be entirely in agreement as to what metrics are suitable for measuring the efficiency of a daylighting strategy on both building performance and occupant's visual comfort, and well-being. To fully understand the success of these buildings, more investigations are required to map human behavior in these buildings. This requires designers to pay more attention to sensitivity analyses related to occupant's view sheds and behavior as well as 2D isovists and visibility within the indoor building layout in order to determine if occupants really do receive adequate daylight, or whether they do not, despite meeting building performance benchmarks. Futures studies could take the occupant experience perspective further. This would include sensitivity studies that document behavioral patterns within the atriums. Behavioral mapping, observations, and occupant's surveys could measure occupants' patterns that could identify experiential human-centered factors in the indoor environment. These provide insights on how building occupants rate the space themselves. This subjective data could reinforce the objective daylight parameter data collected. Or, it could prove that a successfully designed daylit building which performs well in terms of providing enough light for visual task needs as well as circadian rhythm regulation does not necessarily translate to positive occupant experience. The findings could demonstrate, the success of the atrium design lies not only in its daylighting parameters but in the opportunity it creates as an intermediate condition between interior and exterior spaces. Fomenting social activity might be more influenced by the space's furniture, its arrangement, views across space, and proximity to paths. Nonetheless, if the design intent is to create an atrium space to be occupied by building users for extensive periods of time, it is vital for designers to assess the human well-being and biological aspects of daylight in addition to the instrumental metrics. This will help with the considerations for their proper use and pitfalls suggesting that, indeed, atria of one form do not fit all buildings.

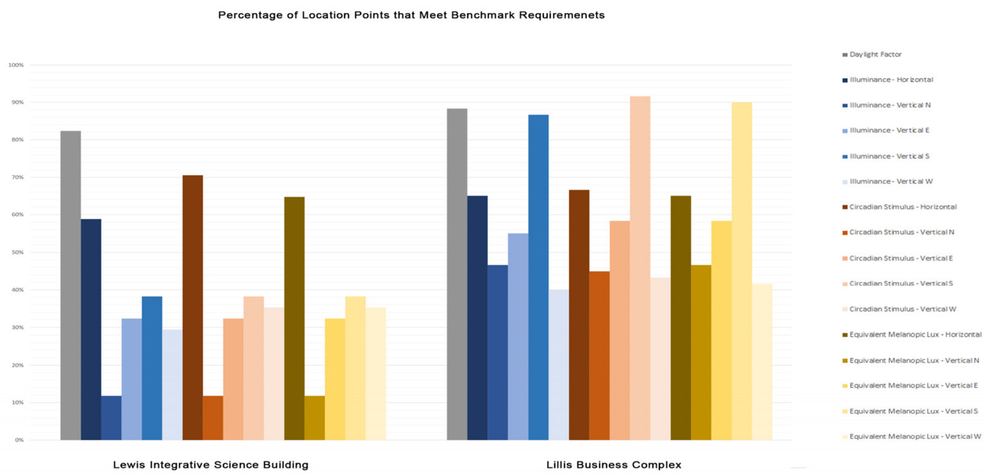

Figure 3. Percentage of location points that meet benchmark requirements (Author, 2019)

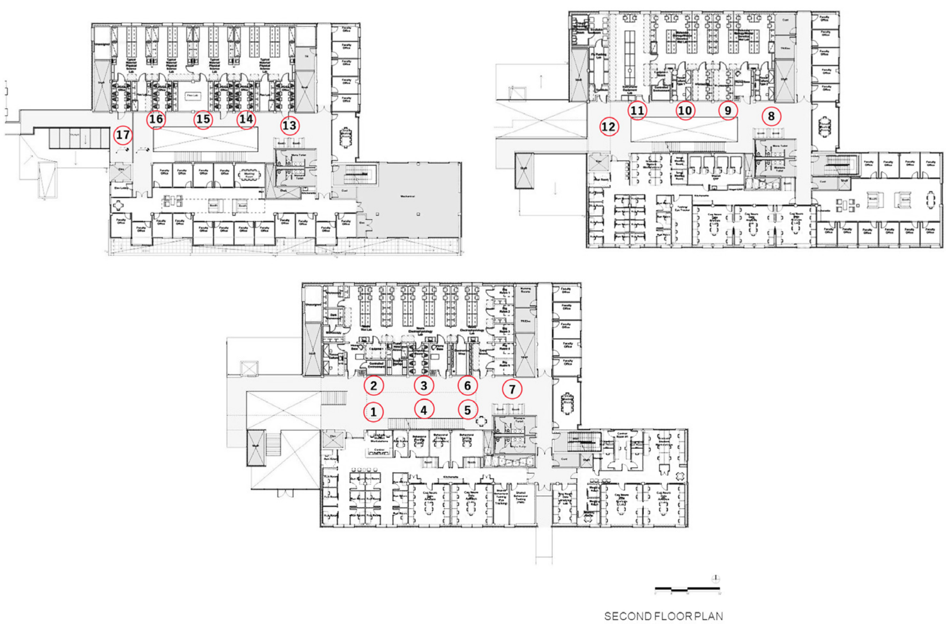

Figure 4. LISB floorplans with measurement location points (Author, 2019)

Table 1. LISB daylight factor and illuminance morning and afternoon measurements (Author, 2019)

Point	DF		Illuminance (lux)									
			Horizontal		Vertical							
					N		E		S		W	
1	4%	2%	273	718	33	79	125	234	20	100	34	195
2	4%	1%	285	332	15	48	122	149	29	115	32	139
3	3%	1%	226	227	15	39	76	74	76	66	33	110
4	5%	1%	367	397	36	41	115	56	36	36	55	220
5	1%	0%	101	152	22	21	18	51	10	31	82	143
6	3%	0%	186	92	6	25	24	86	38	33	70	85
7	1%	0%	70	96	19	18	36	137	25	24	48	53
8	1%	0%	84	105	29	45	46	124	20	50	74	221
9	6%	1%	407	490	31	64	74	100	207	338	128	302
10	8%	2%	552	872	65	118	173	340	232	349	118	300
11	5%	2%	340	614	53	184	201	436	185	436	125	876
12	3%	3%	190	1158	88	2578	72	482	77	374	244	1502
13	18%	5%	1278	2104	136	375	127	592	420	1174	300	760
14	10%	4%	714	1573	121	321	318	637	616	1076	297	575
15	12%	4%	819	1469	95	260	315	728	546	921	259	652
16	10%	2%	692	679	122	215	331	587	541	745	125	707
17	2%	1%	163	578	66	864	201	673	120	351	249	1179

Table 2. LISB circadian stimulus morning and afternoon measurements (Author, 2019)

Point	Circadian Stimulus (CS)									
	Horizontal		Vertical							
			N		E		S		W	
1	0.32	0.5	0.03	0.08	0.18	0.26	0.03	0.17	0.03	0.17
2	0.34	0.38	0.02	0.04	0.18	0.21	0.02	0.1	0.03	0.13
3	0.3	0.31	0.01	0.06	0.09	0.12	0.11	0.06	0.03	0.14
4	0.41	0.4	0.04	0.03	0.16	0.06	0.03	0.05	0.05	0.25
5	0.15	0.18	0.02	0.01	0.02	0.07	0.01	0.03	0.12	0.18
6	0.27	0.14	0.01	0.02	0.02	0.15	0.04	0.02	0.1	0.12
7	0.04	0.12	0.03	0.01	0.05	0.23	0.02	0.03	0.08	0.04
8	0.11	0.15	0.02	0.04	0.06	0.21	0.02	0.03	0.11	0.26
9	0.43	0.47	0.04	0.08	0.12	0.16	0.28	0.39	0.19	0.34
10	0.47	0.55	0.08	0.15	0.23	0.37	0.29	0.37	0.16	0.31
11	0.37	0.48	0.08	0.22	0.27	0.41	0.25	0.4	0.18	0.052
12	0.2	0.54	0.13	0.63	0.09	0.39	0.09	0.34	0.32	0.59
13	0.6	0.64	0.18	0.34	0.018	0.45	0.41	0.57	0.035	0.51
14	0.53	0.62	0.17	0.34	0.34	0.47	0.48	0.56	0.34	0.46
15	0.54	0.61	0.14	0.28	0.36	0.5	0.47	0.54	0.32	0.49
16	0.51	0.51	0.17	0.27	0.36	0.46	0.47	0.52	0.18	0.51
17	0.16	0.42	0.1	0.5	0.25	0.48	0.14	0.37	0.32	0.58

Table 3. LISB equivalent melanopic lux morning and afternoon measurements (Author, 2019)

Point	Equivalent Melanopic Lux (EML)									
	Horizontal		Vertical							
			N		E		S		W	
1	265.8	696.7	26.4	61.3	119	210.8	12	68.7	23.6	149.2
2	284.9	338.5	12.8	34.8	119	144.5	19.8	84.7	23.9	106.6
3	226.1	228.3	11.7	24.3	53.1	70.9	68.9	47.9	25	95.3
4	378.7	385.9	28.8	29	107	44.8	25.8	20.6	42.9	195.4
5	97.1	134.9	16.8	14.5	11.2	49.2	5.4	13	76.4	128.5
6	191.3	88.1	3.9	16.3	18.4	87.7	31.5	21.7	65.3	76
7	41.6	46.1	10.5	11.2	18.2	144.5	9.5	10.3	45.6	35.5
8	42	59.1	19.2	32.6	39.4	127.8	9.2	33.5	70	206.7
9	427.2	519.4	27.9	54.3	70.9	99.8	208.4	347.8	124.6	290.7
10	559.2	906.5	54.4	104.7	176.3	331	224.8	331.7	108.8	269.1
11	330.9	594.3	48.8	166.7	199.3	417.5	181.7	406.9	119.9	805.7
12	152.3	1007.7	83.3	2274.8	63.1	423.5	60.7	322.3	243.6	1358
13	1319.8	2218	127.6	337.8	119.5	554.4	411.6	1132.2	295.3	733.8
14	762.2	1603.1	115	302.3	303.2	601.7	599.3	1057.5	289	554.2
15	832.3	1509	89.9	234.9	314.6	694.3	553.1	898.9	254.7	639.9
16	696.1	697.6	114.4	205.7	324.9	554.9	546	757.6	118.5	701.9
17	122.7	492	62.9	770.5	189.3	636.8	97.4	333.3	247.5	1148.8

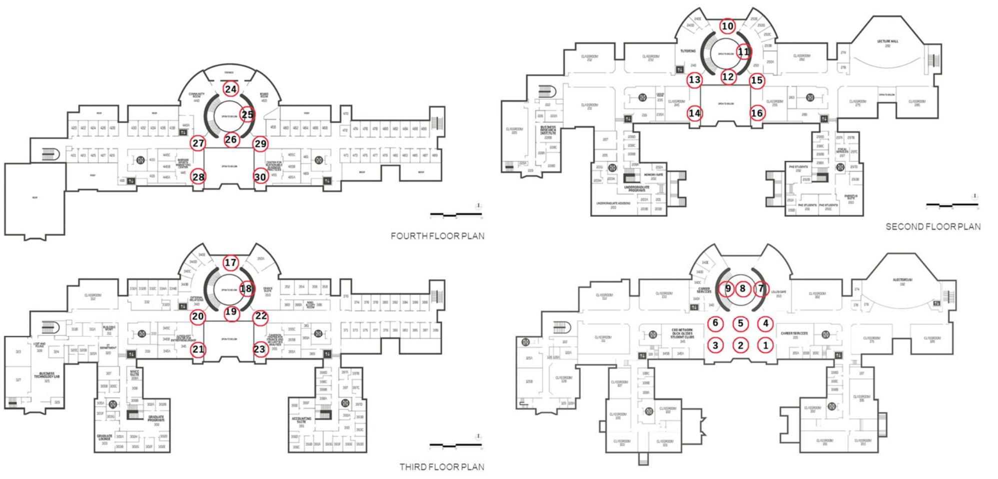

Figure 5. Lillis floorplans with measurement location points (Author, 2019)

Point	DF		Illuminance (lux)										
			Horizontal		Vertical								
					N		E		S		W		
1	12%	8%	1124	1436	193	489	219	830	1379	1314	265	321
2	13%	7%	1254	1272	208	457	174	754	1990	1245	269	245
3	10%	5%	988	924	144	262	294	678	793	762	210	135
4	12%	4%	1199	712	149	164	365	530	1211	971	122	157
5	12%	5%	1145	938	141	154	206	562	1314	1199	199	171
6	11%	4%	1029	806	150	134	117	227	1582	1004	210	271
7	2%	1%	171	158	84	87	21	35	185	234	96	92
8	3%	1%	275	209	101	117	34	55	283	325	59	47
9	2%	1%	242	160	76	91	81	110	180	150	27	27
10	2%	1%	242	211	484	531	122	111	354	307	158	128
11	2%	1%	148	177	117	134	63	72	232	215	227	172
12	8%	2%	771	424	279	238	191	596	2008	1190	213	155
13	2%	1%	218	136	84	82	768	301	893	317	28	42
14	4%	1%	439	173	166	167	926	746	862	439	78	73
15	2%	1%	221	199	97	432	19	381	591	2288	335	331
16	4%	2%	433	406	173	582	86	1574	1947	1127	615	11071
17	2%	0%	161	66	368	256	130	108	1023	331	223	116
18	4%	2%	369	316	228	152	122	88	752	290	637	304
19	12%	2%	1143	388	710	356	369	526	5971	1066	552	234
20	4%	0%	372	86	504	114	1606	388	2597	384	118	53
21	6%	1%	629	232	350	186	1374	915	1654	701	188	205
22	3%	1%	265	216	270	744	59	412	1471	13959	1011	839
23	12%	4%	1158	682	757	514	433	865	3179	9427	1898	18348
24	9%	2%	876	377	1065	633	378	206	1849	592	388	310
25	9%	3%	848	566	655	573	296	618	1041	1171	1157	823
26	16%	4%	1556	665	1216	630	1051	908	4245	1356	1102	573
27	13%	3%	1230	466	648	304	1306	624	2814	687	185	82
28	24%	7%	2318	1197	1751	589	2505	1196	2763	1232	807	430
29	10%	3%	933	547	417	1094	99	485	2736	10548	1085	12383
30	18%	7%	1726	1303	1238	811	495	846	4779	16656	2124	2984

Table 4. Lillis daylight factor and illuminance morning and afternoon measurements (Author, 2019)

Table 5. Lillis circadian stimulus morning and afternoon measurements (Author, 2019)

Point	Circadian Stimulus (CS)									
	Horizontal		Vertical							
			N		E		S		W	
1	0.58	0.59	0.2	0.37	0.24	0.44	0.6	0.61	0.3	0.33
2	0.59	0.6	0.25	0.37	0.22	0.44	0.63	0.62	0.2	0.28
3	0.57	0.56	0.18	0.25	0.33	0.45	0.53	0.56	0.24	0.12
4	0.58	0.51	0.16	0.19	0.36	0.38	0.58	0.58	0.12	0.18
5	0.58	0.56	0.15	0.18	0.22	0.4	0.59	0.6	0.22	0.19
6	0.56	0.52	0.16	0.16	0.11	0.19	0.61	0.59	0.23	0.31
7	0.22	0.21	0.11	0.14	0.02	0.06	0.23	0.33	0.12	0.13
8	0.3	0.22	0.12	0.15	0.03	0.05	0.31	0.4	0.06	0.05
9	0.28	0.2	0.09	0.12	0.09	0.12	0.23	0.21	0.03	0.03
10	0.29	0.36	0.44	0.52	0.15	0.17	0.36	0.37	0.2	0.23
11	0.18	0.23	0.12	0.17	0.04	0.05	0.25	0.26	0.26	0.23
12	0.5	0.43	0.29	0.25	0.2	0.38	0.63	0.59	0.22	0.2
13	0.22	0.16	0.07	0.08	0.4	0.28	0.52	0.36	0.02	0.07
14	0.38	0.19	0.16	0.17	0.53	0.47	0.52	0.47	0.13	0.12
15	0.23	0.14	0.09	0.43	0.03	0.41	0.45	0.62	0.33	0.35
16	0.39	0.28	0.15	0.46	0.14	0.58	0.62	0.58	0.47	0.69
17	0.12	0.05	0.34	0.29	0.13	0.12	0.54	0.36	0.25	0.18
18	0.36	0.34	0.25	0.2	0.15	0.11	0.48	0.32	0.48	0.38
19	0.55	0.41	0.49	0.39	0.33	0.36	0.68	0.58	0.41	0.25
20	0.35	0.07	0.38	0.16	0.57	0.35	0.64	0.39	0.18	0.09
21	0.47	0.2	0.31	0.19	0.6	0.51	0.62	0.5	0.15	0.29
22	0.24	0.18	0.2	0.49	0.04	0.41	0.6	0.69	0.51	0.45
23	0.55	0.49	0.43	0.46	0.43	0.51	0.66	0.68	0.61	0.69
24	0.57	0.49	0.61	0.56	0.41	0.32	0.63	0.49	0.41	0.4
25	0.54	0.48	0.51	0.44	0.33	0.39	0.6	0.54	0.59	0.55
26	0.61	0.52	0.59	0.51	0.55	0.5	0.67	0.6	0.56	0.47
27	0.57	0.37	0.43	0.29	0.59	0.46	0.65	0.48	0.14	0.06
28	0.64	0.54	0.59	0.39	0.64	0.54	0.66	0.56	0.53	0.43
29	0.51	0.36	0.38	0.56	0.08	0.41	0.65	0.68	0.57	0.69
30	0.62	0.55	0.55	0.54	0.44	0.52	0.68	0.69	0.62	0.63

Table 6. Lilllis equivalent melanopic lux morning and afternoon measurements (Author, 2019)

Point	Equivalent Melanopic Lux (EML)									
	Horizontal		Vertical							
			N		E		S		W	
1	1116.4	1346.7	160.2	406.7	190.2	631.4	1354.5	1385.1	247.3	289.7
2	1251.4	1333.7	190.2	385.9	156.8	599.5	1989.5	1513.8	246.1	221.4
3	1010.1	959.7	128	216.1	276.9	575.9	788.4	856.4	185.1	100.1
4	1178.1	697.3	119.7	140.9	329.5	430.7	1186.4	1064.3	92.1	132.7
5	1129.6	948	113.1	130.4	173.5	464.9	1296.3	1311.7	167.1	142.4
6	1008.5	767.8	122.2	113	89.4	168.9	1543.4	1129.7	177.3	252.8
7	175	144.6	71.9	83.2	14.8	19.3	166.4	249.1	82.6	85
8	250.7	174.1	85.2	103.3	23.6	41.4	259.7	346.1	46.5	36.3
9	221.7	142	62.8	81.3	66.2	89.3	164.3	142.1	20.7	21.3
10	222	248.7	471	631	97.7	107.2	331	310.1	139.7	140.4
11	127.7	163.5	89.7	116.6	42.4	50.9	195.2	196.4	205.4	163.8
12	713.3	430.1	242.1	206.4	155.3	471	1920.8	1246.4	177.4	140.2
13	176.9	112.4	62	63.8	417	249.8	806	306.1	18.2	25.1
14	389	144.2	128.7	136.4	865.1	646.6	811.4	484	49.7	44.4
15	183.5	135.1	72.4	287.3	12.6	268.5	539.3	2007	297.5	311.6
16	390.3	290.5	127.6	347.3	76.7	828.5	1873.7	1116.9	592.5	8807.6
17	109.5	44.5	399.9	235.8	101.8	89.5	921.8	323.7	194	115
18	334.7	293.6	200.5	143.9	106.2	78	668.7	275.6	599.8	318
19	1021.6	382.2	655.3	348.8	312.7	415.7	5550.4	1106.6	463	204.3
20	226.7	59.4	415.5	104.4	1296.4	335.7	2392.1	366.9	73.2	33.8
21	781.1	177.4	289	150.6	1343.3	796.8	1631.2	675.8	139.3	139.7
22	207.8	177.8	167.5	418	39.6	263.9	173.7	11310.5	843.4	666.9
23	1004.4	628.8	590.2	339.4	295	493.4	3133	7402.5	1653.4	14300.7
24	960.1	476.4	1286.3	805.3	386.1	250.2	1897.1	599.7	389.5	342.5
25	834.7	578.7	662.8	526.6	279.8	498	1374.2	1005.4	1195.2	868
26	1556.3	693.5	1244.7	657.1	961.5	765.7	4271.6	1376.8	1011.7	561.4
27	1116.1	391.9	538.5	262.2	1206.2	569.1	2694.2	629.6	128.7	55.1
28	2211.9	1020.3	1456.6	474.3	2351.9	1027.2	2931.1	1114.9	535.4	298.7
29	785.2	411.3	374.1	664.2	68	274	2661.4	8013.2	1047.7	9379.2
30	1655.2	1105.4	1042.2	576.4	320.8	517	4748.6	1938.2	1881.7s	12731.5

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