Disparities in circadian potential: the impact of building form and interior wall composition on dynamic light exposure

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Abstract

This paper builds on previous efforts to evaluate and compare dynamic light-exposure profiles over time and across space. This paper examines two office-floor plans through the eye-level exposure of 10 representative occupant profiles as they move throughout a series of seated locations over time. These 10 profiles are then used to create a weighted score for the full population of building occupants by applying the performance of each representative profile to the number of similar profiles in that occupant class. This allows us to compare the percentage of occupants that are expected to meet the WELL v2 Feature L03 150 EML target at a building scale, while also accounting for typical use patterns and advocating for the importance of dynamic behavior. The findings presented in this paper illustrate the impact of building form, interior material, and typical occupancy scenarios on non-visual health across a dynamic occupant population.

Highlights

- Evaluating circadian light exposure for dynamic occupancy schedules
- Weighted approach to evaluating EML across occupant narratives
- Evaluating WELL v2 Feature L03 over space and time

Introduction

Recent research has revealed the importance of eye-level light exposure for aligning sleep-wake cycles with the solar day and promoting circadian health in day active people. Over the past few centuries, humans have shifted the composition of their daily eye-level light exposure as they've moved from outdoor work environments to indoor office spaces. Compared to the intensity of outdoor illumination, light exposure in the indoor workplace is most often characterized by a brighter, daylit perimeter and a dimmer, electrically lit core. This spatial discrepancy in luminous conditions creates the potential for inequities in eye-level light exposure between occupants who populate the building perimeter and the building core (Rockcastle et al, 2020; Rea et al., 2018). Electric lighting systems can help supplement deficient exposure levels, but previous research has revealed that ceiling mounted, and suspended LED lighting systems (typical in offices) can fall short of meeting recommended Equivalent Melanopic Lux (EML) thresholds for many building occupants, even when they meet recommended horizontal task illuminance thresholds (Danell et al, 2021; Safranek et al, 2023). This paper builds on past research to compare the impact of building form and interior wall transparency on a sample of occupant profiles as they move throughout a typical daily routine. These profiles are used to extrapolate light exposure trends to the population of occupants using a weighted score.

The results reveal that building form, partition transparency, and desk location impact the number of occupants that achieve recommended eye-level light exposure between the hours of 8am-3pm (the range of hours that can be used towards meeting the WELL v2 2022 standard). Furthermore, individual occupant profiles vary substantially in their access to recommended light exposure levels from daylight as they move in and out of light deprived zones over time, This reveals that supplemental electric lighting is required for a majority of occupants to meet circadian dosing recommendations. As discussed by Abboushi et al., 2021 and Danell et al, 2021, overhead lighting systems (ubiquitos to the office environment) were designed to deliver lux on a horizonatl task plane, not equivalent melanopic lux at the eye. Safranek et al., 2023 predicted that we will need 3x the light at eye-level than what is typically recommended for visual taks recorded on a horizontal plane. Until we have interior lighting systems that are designed to meet this dual demand, occupants who rely on electric lighting to supplement their daily light intake are at risk of under-exposure, leading to circadian health inequities over time.

Background

As the body of circadian knowledge grows, there have been a range of new models to quantify the effect of eye-level light exposure on occupant health in buildings. In 2014, Lucas et al. proposed a metric called Equivalent Melanopic Lux (EML), which normalizes the melanopic luminous efficacy curve to correspond with the photopic curve. EML weighs photoreceptors involved in non-visual functions (Lucal et al., 2014). Melanopic Equivalent Daylight Illuminance (M-EDI) is a related circadian metric, adopted by the International Commission on Lighting (2018). It represents an equivalent lux of natural light (D65) needed to obtain the same melanopic lux of a given source. The Lighting Research Center (LRC) developed the Circadian Stimulus (CS) to determine the effectiveness of different light sources and light levels in maintaining a healthy circadian rhythm (Rea et al., 2010).

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While there are several approaches to calculate the melanopic or circadian effectiveness of a light source, the WELL Building Standard is one of the only rating systems that awards points to a building design that meets specified light exposure thresholds for workspaces. To receive 1-point, the WELL v2 Q4, 2022 standard for Feature L03 (Circadian Lighting Design) requires a minimum of 150 equivalent melanopic lux (EML) or 136 M-EDI (D65) for all workstations, maintained for a minimum of four hours beginning by noon at the latest (WELL Q4, 2022). To receive 2-points, the standard requires a minimum of 275 equivalent melanopic lux (EML) or 250 M-EDI (D65). In 2017, Amundadottir et al. developed a novel mathematical model (nvRD) to predict the non-visual effects of light exposure and compute a cumulative daily light dose. This method uses rendered 360-degree images across a series of 180-degree view directions to analyze the non-visual daylight performance. Later, Rockcastle et al (2018) used the same method to expand the workflow from a single view position to a spatial analysis to evaluate an array of view directions over time.

There is a dynamic interaction between a building and its occupants (Langevin, 2019), but occupant behavior is often disregarded or simplified as a static schedule in daylight performance simulation. It is difficult to fully understand the complete mechanism of occupant behavior due to its complex and uncertain nature (Yan et al., 2015). Several methods have been developed to incorporate human behavior into models for evaluating building performance (Shen et al., 2012; Yan et al., 2015; Schaumann et al., 2015). Typical lighting simulation tools and metrics evaluate daylight performance across a grid of fixed positions, but building occupants move over time and this dynamic behavior exposes them to various levels of light across space and over time. To understand the impact of an occupants' dynamic behavior on light exposure, Danell et al. (2020) proposed a novel method based on the simulation workflow developed by Amundadottir et al. (2017). They used four occupant profiles in a side-lit office case study to compute the user's light exposure during the day. The results highlight the impact of considering spatial and temporal behavior on the performance of daylight for human-centric metrics. Rockcastle et al. (2020) followed a similar approach to examine how an occupant's behavior affects their circadian light exposure under daylight and electric lighting sources. The results identified the relative impact of electric lighting on cumulative healthy light exposure. The findings of this study showed different results between the WELL standard and nvRD model due to the timing criteria (9am-1pm) applied in the WELL Q4 2020 Standard, but both revealed that overhead electric lighting systems were unable to meet eye-level exposure requirements for a majority of building occupants.

The paper presented here builds on previous efforts to evaluate and compare dynamic light-exposure profiles over time and across space. This paper examines two office-floor plans through the eye-level exposure of 10 representative occupant profiles as they move between a series of seated locations over time. These 10 profiles are then used to create a weighted score for the full occupant population by applying the performance of each representative profile by the number of similar profiles in that same class. This allows us to compare the percentage of occupants that are expected to meet the WELL v2 Feature L03 150 EML target at a building scale, while also accounting for typical use patterns and pushing the WELL standard to account for dynamic behavior.

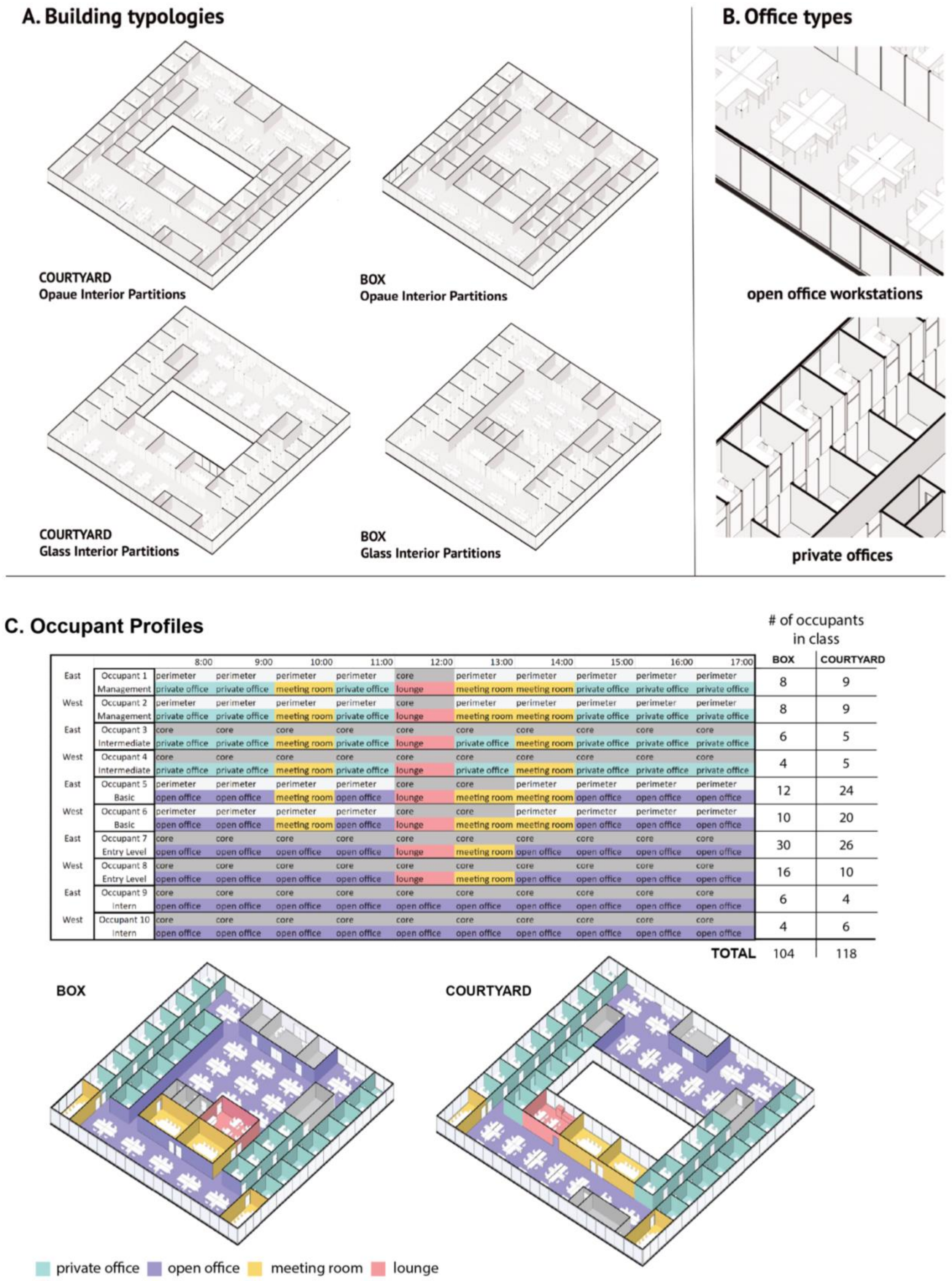
Methods

This paper uses an occupant-centric approach to simulate Equivalent Melanopic Lux or 'EML' (Lucas et al, 2014) for seated positions in an office building. The authors have created two typological building forms (box and courtyard), two interior wall conditions (opaque and glazed) and two office types (private enclosed and open office) to draw comparisons. EML has been simulated at eye-level using a Radiance-based workflow, with daylight values calculated using a standard 3-channel approach, weighted to standard illuminant D65 (from 8am-5pm on June 21, September 22, and December 21). Electric light can be added to a space to supplement deficient daylight exposure levels and still achieve WELL v2 Q4 2022 (Feature L03), but rather than simulate a single electric lighting design throughout the space and add it to our daylight values, the authors report the EML achieved using daylight only (circadian daylight potential) and calculate the number of hours that supplemental light would be needed (required electric lighting). This allows us to compare the portion of an occupant's daily light exposure that would be met by daylight to the portion that would require supplemental sources, revealing disparities in daylight equity.

To understand the circadian light potential across a sample population of building occupants, we generated a series of occupant profiles using similar scheduling rules for each building typology (box and courtyard). These profiles were then used to generate typical daily light exposure levels for each occupant and allow us to compare the impact of building form, wall transparency, seating location, and spatial behavior on recommended eye-level light exposure thresholds (EML 150 as defined by the WELL Building Standard v2 Feature L03, 2022 for 1-credit).

Office Typologies

To demonstrate this concept, the authors have created two office floor-plan typologies that vary in daylight access within the building core: box and courtyard (Figure 1A). Both typologies consist of a perimeter line of private offices facing East and West and a secondary line of private offices just across the hallway towards the building core. The box plan has an exterior dimension of 100 ft x 100 ft and the courtyard plan is 110 ft x 100 ft.



		8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	# of occupants in class BOX	COURTYARD
East	Occupant 1	perimeter	perimeter	perimeter	perimeter	core	perimeter	perimeter	perimeter	perimeter	perimeter	8	9
	Management	private office	private office	meeting room	private office	lounge	meeting room	meeting room	private office	private office	private office		
West	Occupant 2	perimeter	perimeter	perimeter	perimeter	core	perimeter	perimeter	perimeter	perimeter	perimeter	8	9
	Management	private office	private office	meeting room	private office	lounge	meeting room	meeting room	private office	private office	private office		
East	Occupant 3	core	core	core	core	core	core	core	core	core	core	6	5
	Intermediate	private office	private office	meeting room	private office	lounge	private office	meeting room	private office	private office	private office		
West	Occupant 4	core	core	core	core	core	core	core	core	core	core	4	5
	Intermediate	private office	private office	meeting room	private office	lounge	private office	meeting room	private office	private office	private office		
East	Occupant 5	perimeter	perimeter	perimeter	perimeter	core	core	perimeter	perimeter	perimeter	perimeter	12	24
	Basic	open office	open office	meeting room	open office	lounge	meeting room	meeting room	open office	open office	open office		
West	Occupant 6	perimeter	perimeter	perimeter	perimeter	core	core	perimeter	perimeter	perimeter	perimeter	10	20
	Basic	open office	open office	meeting room	open office	lounge	meeting room	meeting room	open office	open office	open office		
East	Occupant 7	core	core	core	core	core	core	core	core	core	core	30	26
	Entry Level	open office	open office	open office	open office	lounge	meeting room	open office	open office	open office	open office		
West	Occupant 8	core	core	core	core	core	core	core	core	core	core	16	10
	Entry Level	open office	open office	open office	open office	lounge	meeting room	open office	open office	open office	open office		
East	Occupant 9	core	core	core	core	core	core	core	core	core	core	6	4
	Intern	open office	open office	open office	open office	open office	open office	open office	open office	open office	open office		
West	Occupant 10	core	core	core	core	core	core	core	core	core	core	4	6
	Intern	open office	open office	open office	open office	open office	open office	open office	open office	open office	open office		
											TOTAL	104	118

Figure 1: A. Shows the two building typologies (courtyard and box) and the two interior wall conditions (opaque and glass). B. Shows the two office types (open and private). C. Shows ten exemplary occupant profiles from intern to management.

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Open clusters of shared workstations populate the zones between the private offices on both the North and South sides of the buildings. Two sets of meeting rooms have been placed within the perimeter and core zones as well as a lounge space within the core, where some occupants take their lunch break. Both building typologies consist of roughly the same interior floor area (10,000 SF for the box and 10,300 SF for the courtyard). Two interior wall conditions have also been modelled between the private perimeter and core offices: interior glass and opaque solid partitions. Exterior glass walls (and interior glass partitions, where applicable) run floor-to-ceiling with an 8’-0” ceiling height. Material reflectances are shown in Table 1.

Occupant Profiles

To compare light-exposure profiles between occupants, two types of office seating have been created: open and private (Figure 1B). While there are differences in the exact number of seating positions by office type between the box and the courtyard, there is a similar proportion of open (78 in the box/90 in the courtyard) and private seating positions (26 in the box/28 in the courtyard) in each. Ten occupant profiles have been created to produce a range of typical office workers that cover each of our building zone conditions (private perimeter E/W, private core E/W, open perimeter N/S, and open core N/S). These profiles illustrate a range of hierarchies typically present in an office workplace environment in the United States, with more upper-level employees having access to a private perimeter office and preferential booking of meeting spaces that have better daylight penetration. Figure 1C shows a colored overview of these profiles to distinguish open (purple) vs. private (teal) office types as well as meeting rooms (yellow) and lounge spaces (red).

Simulation Overview

The workflow in this paper uses Radiance to compute EML at eye-level across a range of view positions and view directions. There is ongoing work that compares 3-channel, 9-channel, and even 81-channel Radiance simulations to compare the accuracy of EML values, revealing that more channels result in more accurate EML calculations, particularly when electric lighting is the primary source of illumination. Electric light sources generally produce a lower intensity of eye-level illumination than daylight and higher spectral resolution is more critical when intensities are lower. In other words, a 3-channel simulation has been described as sufficient for daylight-driven sources, where 9-channel and even 81-channel simulations are preferred when electric lighting is introduced (Abboushi et al, 2021). As the authors in this study have chosen to simulate EML from daylight sources only and discuss supplemental dose as a demand, we chose a 3-channel simulation because it allows us to compare daily dose profiles in relative terms using a reproducible workflow. Future work will seek to integrate a more costly 9-channel approach to improve the accuracy.

Simulation Workflow

Each of our building forms (box and courtyard) and interior wall types (opaque and glass) were modelled in Rhino, with view positions created at seated eye-level (44 inches from the ground) for each desk and chair position. Models and view positions were then exported to Radiance using the workflow presented by Amundadottir et al., 2018. All materials were greyscale and assigned by layer as shown in Table 1. For each view position in the model, RADIANCE v5.2 was used to compute EML across 8 radial view directions for 10 hourly timesteps (8am-5pm) on June 21, September 21, and December 21, under both clear and overcast sky conditions.

Table 1: Radiance Materials

	REFLECTANCE	VLT
interior walls	50%	
ceiling	70%	
floor	20%	
Interior glazing		70%
exterior glazing		70%
mullions	70%	
furniture	50%	

Results

Our results are outlined in the following three sections: the impact of occupant behavior and class on eye-level light exposure over time, the use of a weighted score to expand our sample profiles to predicted WELL v2 Feature L03 compliance for all occupants, and the impact of interior wall opacity on circadian daylight performance and electric lighting demand *between* occupants.

Impact of occupant behaviour and class on EML

Figure 2 shows the results for eye-level EML for each occupant (1-10) from 8am – 5pm on June 21, September 21, and December 21 under clear and overcast skies. This data matrix reports hourly EML values, with light green indicating hourly timesteps thay exceed the 150 threshold, grey indicating timesteps that fell short, and lime green bands highlighting instances when an occupant achieved the WELL recommended 4-hours of continuous exposure starting by 12pm at the latest. While these results do not integrate electric lighting (and it could be assumed that the addition of these light souces would supplement eye-level EML to meet the recommended target), they reveal when and for whom that supplement is required. Occupants 1-2, who spend a majority of their day at desks in a perimeter private office, manage to meet the required 4-hour dose window under clear skies in all four design scenarios. Occupants 3-4 populate a set of private offices towards the building core and received adequate exposure in the courtyard variant, but fall short in the box variant where opaque walls cut off access to the East and West facades. Occupants 5 and 6 also perform relatively well, where a seated desk position closer to the perimeter provides good circadian access in the open-office zones, although occupant 6 has a shifted performance window due to their position on the North-side of the building, where EML levels are lower in the mornings.

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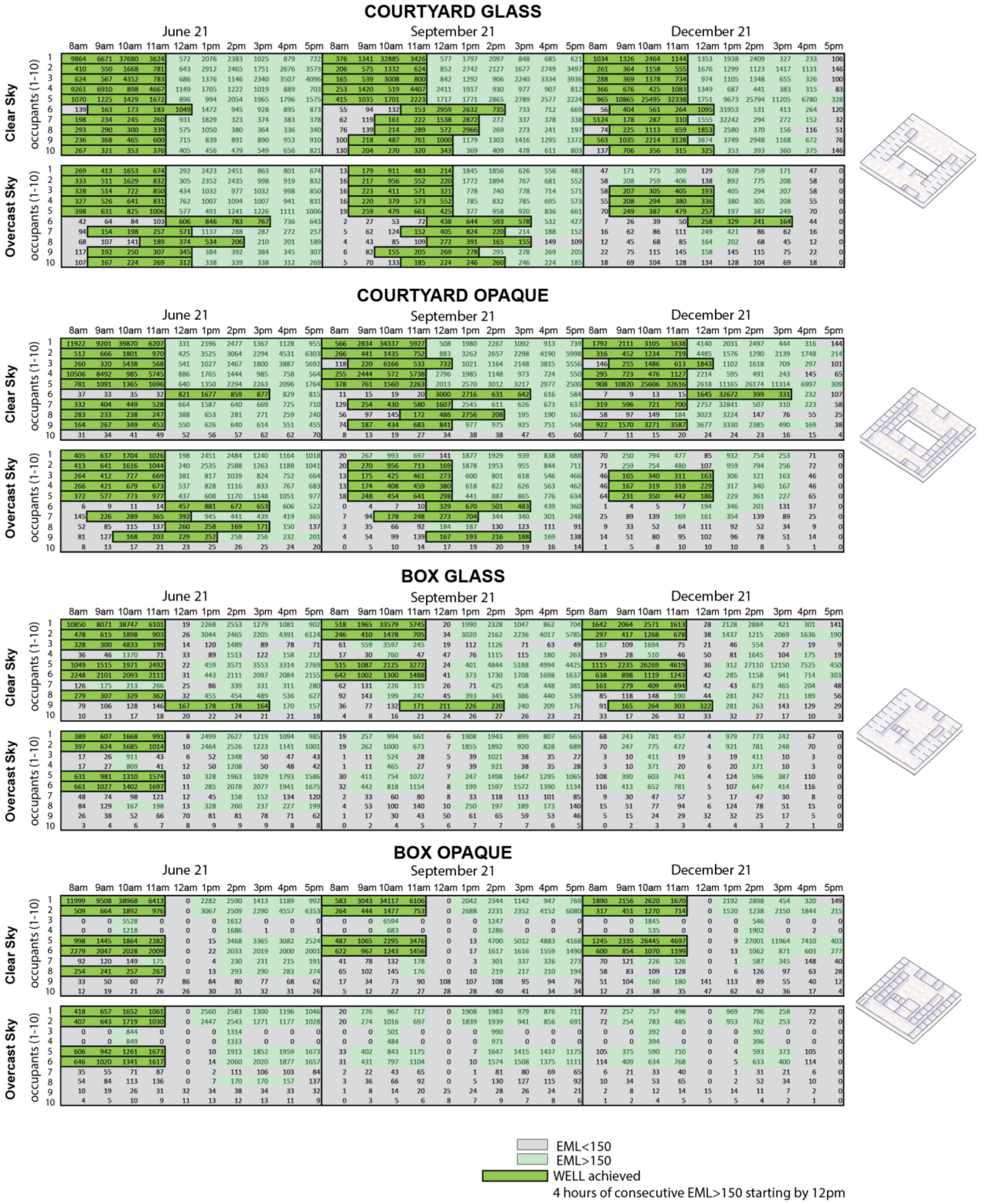

COURTYARD GLASS

	occupants (1-10)	June 21										September 21										December 21									
		8am	9am	10am	11am	12am	1pm	2pm	3pm	4pm	5pm	8am	9am	10am	11am	12am	1pm	2pm	3pm	4pm	5pm	8am	9am	10am	11am	12am	1pm	2pm	3pm	4pm	5pm
Clear Sky	1	9864	6671	37680	3624	572	2076	2383	1025	879	722	376	1341	32885	3426	577	1797	2097	848	685	621	1034	1326	2464	1144	1353	1938	2409	327	233	106
	2	410	550	1668	781	643	2912	2465	1751	2676	3573	206	575	1332	624	852	2742	2127	1677	2749	3497	261	364	1158	555	1676	1299	1123	1417	1131	146
	3	624	567	4352	783	686	1376	1146	2340	3507	4096	165	539	3008	800	842	1292	906	2240	3334	3936	288	369	1378	734	974	1105	1348	655	326	100
	4	9261	6910	898	4667	1149	1705	1222	1019	889	703	253	1420	519	4407	2411	1917	930	977	907	812	366	676	425	1083	1349	687	441	383	315	83
	5	1070	1225	1429	1672	896	994	2054	1965	1796	1575	415	1035	1701	2223	1717	1771	2865	2789	2577	2224	965	10865	25495	32338	1751	9673	25794	11205	6780	328
	6	139	163	173	183	1049	1472	945	928	895	873	55	94	132	153	2959	2632	735	733	712	669	56	404	561	264	1095	31953	531	413	264	120
	7	198	234	245	260	931	1829	323	374	383	378	62	119	161	222	1538	2872	272	337	378	338	5124	178	287	310	1555	32242	294	272	152	32
	8	293	290	300	339	575	1050	380	364	336	340	76	139	214	289	572	2966	269	273	241	197	74	225	1113	659	1853	2580	370	156	116	51
	9	236	368	465	600	715	839	891	890	953	910	100	218	487	761	1000	1179	1303	1416	1295	1372	563	1035	2214	3128	3874	3749	2948	1168	672	76
	10	267	321	353	376	405	456	479	549	656	821	130	204	270	320	343	369	409	478	611	803	137	706	356	315	325	353	393	360	375	146
Overcast Sky	1	269	413	1653	674	292	2423	2451	863	801	674	13	179	911	483	214	1845	1856	626	556	483	47	171	775	309	129	928	759	171	47	0
	2	333	511	1629	832	305	2352	2435	998	919	832	16	217	956	552	220	1772	1894	767	681	552	58	208	759	406	138	892	775	208	58	0
	3	328	514	722	850	434	1032	977	1032	998	850	16	223	411	571	321	778	740	778	714	571	58	207	305	405	193	405	294	207	58	0
	4	327	526	641	831	762	1007	1094	1007	941	831	16	220	379	573	552	785	832	785	695	573	55	208	294	380	336	380	305	208	55	0
	5	398	631	825	1006	577	491	1241	1226	1111	1006	19	259	479	661	425	377	958	920	836	661	70	249	387	479	257	197	387	249	70	0
	6	42	64	84	103	606	846	783	767	736	643	2	27	53	72	438	644	593	578	532	427	7	26	39	50	258	329	241	164	44	0
	7	94	154	198	257	571	1137	288	287	272	257	5	62	124	152	405	824	220	214	188	152	16	62	86	111	249	421	86	62	16	0
	8	68	107	141	189	374	534	206	210	201	189	4	43	85	109	272	391	165	155	149	109	12	45	68	85	164	202	68	45	12	0
	9	117	192	250	307	345	384	392	384	345	307	6	82	155	205	269	278	295	278	269	205	22	75	115	145	158	145	115	75	22	0
	10	107	167	224	269	312	338	339	338	312	269	5	70	133	185	224	246	260	246	224	185	18	69	104	128	134	128	104	69	18	0

COURTYARD OPAQUE

	occupants (1-10)	June 21										September 21										December 21									
		8am	9am	10am	11am	12am	1pm	2pm	3pm	4pm	5pm	8am	9am	10am	11am	12am	1pm	2pm	3pm	4pm	5pm	8am	9am	10am	11am	12am	1pm	2pm	3pm	4pm	5pm
Clear Sky	1	11922	9201	39870	6207	331	2196	2477	1367	1128	955	566	2834	34337	5927	508	1980	2267	1092	913	739	1792	2111	3105	1638	4140	2031	2497	444	316	144
	2	512	666	1801	970	425	3525	3064	2294	4531	6303	266	441	1435	752	883	3262	2657	2298	4190	5998	316	452	1234	719	4485	1576	1290	2139	1748	214
	3	260	320	5438	568	541	1027	1467	1800	3887	5692	118	220	6166	533	732	1021	1164	2148	3815	5556	146	255	1486	613	1843	1102	1618	709	297	101
	4	10506	8492	985	5745	886	1765	1444	985	758	564	255	2444	572	5738	2796	1985	1148	973	724	550	295	723	476	1127	2214	595	491	243	145	65
	5	781	1091	1365	1696	640	1350	2294	2263	2096	1764	378	761	1560	2263	2013	2570	3012	3217	2977	2500	908	10820	25606	32616	2618	11165	26174	11314	6997	309
	6	37	33	35	32	821	1677	859	877	829	815	11	15	19	20	3000	2716	631	642	616	584	7	9	13	15	1645	32672	399	331	232	107
	7	332	404	449	528	664	1587	640	669	725	710	129	254	430	580	1607	2545	611	626	673	637	319	596	721	700	2757	32841	507	310	223	58
	8	283	233	238	247	388	653	281	271	259	240	56	97	145	172	486	2756	208	195	190	162	58	97	149	184	3023	3224	147	76	55	25
	9	164	267	349	453	550	626	640	614	551	455	74	187	434	683	841	977	975	925	751	548	922	1570	3271	3587	3677	3330	2385	490	169	38
	10	31	34	41	49	52	56	57	62	62	70	8	13	19	27	34	38	38	47	45	60	7	11	15	20	24	24	23	16	15	4
Overcast Sky	1	405	637	1704	1026	198	2451	2484	1240	1164	1018	20	267	993	697	141	1877	1929	939	838	688	70	250	794	477	85	932	754	253	71	0
	2	413	641	1616	1044	240	2535	2588	1263	1188	1041	20	270	956	713	169	1878	1953	955	844	711	71	259	754	480	107	959	794	256	72	0
	3	264	412	727	669	381	817	1039	824	752	664	13	175	425	461	273	600	801	618	546	466	46	165	340	311	163	306	321	163	46	0
	4	266	421	679	673	537	828	1116	833	767	683	13	174	408	459	380	618	822	626	563	462	46	167	319	318	229	317	340	167	46	0
	5	372	577	773	977	437	608	1170	1148	1051	977	18	248	454	641	298	441	887	865	776	634	64	231	350	442	186	229	361	227	65	0
	6	6	9	11	14	457	881	672	653	606	522	0	4	7	10	329	670	501	483	439	360	1	4	5	7	194	346	201	131	37	0
	7	145	226	289	365	392	945	441	439	419	365	7	94	178	248	273	704	344	340	301	248	25	89	139	169	161	354	139	89	25	0
	8	52	85	115	137	260	258	169	171	150	137	3	35	66	92	184	187	130	123	111	91	9	33	52	64	111	92	52	34	9	0
	9	81	127	168	203	229	252	258	256	232	201	4	54	99	139	167	193	216	188	169	138	14	51	80	95	102	96	78	51	14	0
	10	8	13	17	21	23	25	26	25	24	20	0	5	10	14	17	19	20	19	16	14	1	5	8	10	10	10	8	5	1	0

BOX GLASS

	occupants (1-10)	June 21										September 21										December 21									
		8am	9am	10am	11am	12am	1pm	2pm	3pm	4pm	5pm	8am	9am	10am	11am	12am	1pm	2pm	3pm	4pm	5pm	8am	9am	10am	11am	12am	1pm	2pm	3pm	4pm	5pm
Clear Sky	1	10850	8071	38747	6101	19	2268	2553	1279	1081	902	518	1965	33579	5745	20	1990	2328	1047	862	704	1642	2064	2571	1613	28	2128	2884	421	301	141
	2	478	615	1898	903	26	3044	2465	2205	4391	6124	246	410	1478	705	34	3020	2162	2236	4017	5785	297	417	1268	678	38	1437	1215	2069	1636	190
	3	328	300	4833	199	14	120	1489	89	78	71	61	559	3597	245	19	112	1126	71	63	49	167	109	1694	75	21	46	554	27	19	9
	4	36	46	1370	71	33	89	1513	122	158	212	17	30	760	47	47	76	1115	115	180	263	19	28	510	46	50	81	1645	104	175	19
	5	1049	1515	1971	2492	22	459	3571	3553	3314	2769	515	1087	2125	3272	24	401	4844	5188	4994	4425	1115	2235	26269	4619	36	312	27110	12150	7525	450
	6	2248	2101	2093	2111	31	443	2111	2097	2084	2155	642	1002	1300	1488	41	373	1730	1708	1698	1637	638	898	1119	1243	42	285	1158	941	714	303
	7	126	175	213	266	25	86	339	331	311	280	62	131	226	315	26	71	425	458	448	381	161	279	409	494	42	43	673	465	204	48
	8	279	307	329	362	32	455	454	489	536	627	92	143	199	242	45	393	345	386	440	539	85	118	148	190	44	281	247	211	189	56
	9	79	106	128	146	167	178	178	164	170	157	36	77	132	171	211	226	220	240	209	176	91	165	264	303	322	281	263	143	129	29
	10	10	13	17	18	20	22	24	21	21	18	4	8	16	21	24	26	27	26	23	21	33	17	26	32	33	32	27	17	10	3
Overcast Sky	1	389	607	1668	991	8	2499	2627	1219	1094	985	19	257	994	661	6	1908	1943	899	807	665	68	243	781	457	4	979	773	242	67	0
	2	397	624	1685	1014	10	2464	2526	1223	1141	1001	19	262	1000	673	7	1855	1892	920	828	689	70	247	775	472	4	921	781	248	70	0
	3	17	26	911	43	6	52	1348	50	47	43	1	11	524	28	5	39	1021	38	35	27	3	10	411	19	3	19	411	10	3	0
	4	17	27	809	41	12	50	1208	50	48	42	1	11	465	27	9	39	921	38	35	28	3	10	371	20	6	20	371	10	3	0
	5	631	981	1310	1574	10	328	1963	1929	1793	1586	30	411	754	1072	7	247	1498	1647	1295	1065	108	390	603	741	4	124	596	387	110	0
	6	661	1027	1402	1697	11	285	2078	2077	1941	1675	32	442	818	1154	8	199	1597	1572	1390	1134	116	413	652	781	5	107	647	414	116	0
	7	48	74	98	121	12	45	158	152	134	120	2	33	60	80	8	33	118	113	101	85	9	30	47	57	5	17	47	30	8	0
	8	84	129	167	198	13	328	260	237	227	199	4	53	100	140	10	250	197	189	173	140	15	51	77	94	6	124	78	51	15	0
	9	26	38	52	66	70	81	81	78	71	62	1	17	30	43	50	61	65	59	53	46	5	15	24	29	32	32	25	17	5	0
	10	3	4	6	7	8	9	9	9	8	8	0	2	4	5	6	7	7	7	6	5	0	2	3	3	4	4	3	2	1	0

BOX OPAQUE

	occupants (1-10)	June 21										September 21										December 21									
		8am	9am	10am	11am	12am	1pm	2pm	3pm	4pm	5pm	8am	9am	10am	11am	12am	1pm	2pm	3pm	4pm	5pm	8am	9am	10am	11am	12am	1pm	2pm	3pm	4pm	5pm
Clear Sky	1	11999	9508	38968	6413	0	2282	2590	1413	1189	992	583	3043	34117	6106	0	2042	2344	1142	947	769	1890	2156	2620	1670	0	2192	2898	454	320	149
	2	509	664	1892	976	0	3067	2509	2290	4557	6353	264	444	1477	753	0	2688	2231	2352	4152	6080	317	451	1270	714	0	1520	1238	2150	1844	215
	3	0	0	5528	0	0	0	1612	0	0	0	0	0	6594	0	0	0	1247	0	0	0	0	0	1845	0	0	0	546	0	0	0
	4	0	0	1218	0	0	0	1686	1	0	1	0	0	683	0	0	0	1286	0	0	2	0	0	535	0	0	0	1902	0	2	0
	5	998	1445	1864	2382	0	15	3468	3365	3082	2524	487	1065	2295	3476	0	13	4700	5012	4883	4168	1245	2335	26445	4697	0	9	27001	11964	7410	403
	6	2279	2047	2028	2009	0	22	2033	2019	2000	2001	622	967	1243	1456	0	17	1617	1616	1559	1490	600	854	1070	1199	0	13	1062	871	603	277
	7	92	120	149	175	0	4	230	231	215	191	41	78	132	178	0	3	301	337	326	273	70	121	226	326	0	1	587	345	148	40
	8	254	241	257	267	0	13	293	290	283	274	65	102	145	176	0	10	219	217	210	194	58	83	109	128	0	6	126	97	63	28
	9	33	50	60	77	86	84	80	77	68	62	17	34	73	90	108	107	108	95	94	76	51	104	160	180	141	113	89	55	40	12
	10	12	19	21	26	26	30	31	32	31	26	5	12	22	27	28	28	40	41	34	34	12	23	38	35	47	62	62	36	17	4
Overcast Sky	1	418	657	1652	1061	0	2560	2583	1300	1196	1046	20	276	967	717	0	1908	1983	979	876	711	72	257	757	498	0	969	796	258	72	0
	2	407	643	1719	1030	0	2447	2543	1271	1177	1028	20	274	1016	697	0	1839	1939	941	856	691	72	254	783	485	0	953	762	253	72	0
	3	0	0	844	0	0	0	1314	0	0	0	0	0	501	0	0	0	990	0	0	0	0	0	392	0	0	0	392	0	0	0
	4	0	0	849	0	0	0	1313	0	0	0	0	0	484	0	0	0	971	0	0	0	0	0	394	0	0	0	396	0	0	0
	5	606	942	1261	1673	0	10	1913	1852	1959	1673	33	402	843	1175	0	7	1647	1415	1437	1175	105	375	590	710	0	4	593	373	105	0
	6	646	1020	1341	1617	0	14	2060	2020	1877	1657	31	431	797	1104	0	10	1574	1508	1375	1111	114	409	634	768	0	5	633	400	114	0
	7	35	55	71	87	0	2	111	106	103	84	2	22	43	65	0	1	81	80	69	65	6	21	33	40	0	1	31	21	6	0
	8	54	84	113	136	0	7	170	170	157	137	3	36	66	92	0	5	130	127	115	92	10	34	53	65	0	2	52	34	10	0
	9	10	19	26	31	32	34	38	34	33	32	1	8	14	20	25	24	28	26	24	21	2	8	12	14	15	14	11	7	2	0
	10	4	5	10	9	11	13	12	13	11	9	0	3	5	6	8	7	9	7	8	6	1	2	4	5	5	5	4	2	1	0

EML<150
EML>150
WELL achieved
4 hours of consecutive EML>150 starting by 12pm

Figure 2: Shows EML for occupants 1-10 (y-axis) as they move around throughout their defined schedule on June 21, September 21, and December 21 between 8am – 5pm (x-axis) under clear and overcast skies. Timesteps that meet or exceed the 150 EML threshold are shown in light green and 4 continuous morning hours of 150-or-greater EML exposure are highlighted in lime green to indicate that that occupant achieved the WELL-recommended criteria.

The WELL v2 standard considers 12-3pm a valid window of exposure to meet the standard, although more research is needed to validate this. The results reveal that occupants 1-5 (in the courtyard variant) receive the highest EML exposure, starting by 8am or 9am at the latest under clear skies. It is interesting to note that exposure levels are sufficient for many occupants when they are located in a private office space, but when their schedule takes them to light deprived meeting or lounge space, their exposure profile drops. This same narrative is revealed in the box variants (both glass and opaque solid), where nearly all occupants experience a substantial drop in EML when eating lunch in the lounge room, which is located more than 14 meters from the façade. For those occupants that lack adequate exposure at their desk beginning at 8am (everyone except for occupants 1-2 and 5-6), a drop in EML at lunchtime removes their ability to achieve a 4-hour window of morning light exposure. Increasing the intensity of light in areas that are frequently visited throughout the day – like the lounge (morning coffee breaks and lunch), could have a substantial impact on non-visual health across a population. These spaces are sometimes located in the building core, adjacent to a plumbing wall, and have not been traditionally seen as spaces that promote health.

A weighted approach to predict WELL performance

This section introduces an approach for predicting the percentage of occupants that met the 150 EML threshold for at least 4 continuous hours (starting by noon at the latest). To achieve this, we use a weighted approach, whereby the performance of each profile (and building type/partition type) is multiplied by the number of occupants that share the same class (as defined by their desk position). Figure 1C shows a breakdown of those numbers on the right-side, revealing the exact number of occupants that share the same occupancy schedule as the sample profile. Figure 3 shows the results of that weighted score for both clear and overcast skies. This graph illustrates a clear narrative about the impact of interior wall transparency on the percentage of occupants that receive adequate eye-level exposure to promote non-visual health. The courtyard plan clearly outperforms the box plan, but the impact of adding glass partitions offers an additional boost in performance, allowing more occupants to achieve a 4-hour window of 150 EML exposure. In the box plan, the glass partitions improved the number of occupants that met the WELL exposure criteria under clear skies, allowing daylight to travel farther from the façade to the building core. Adding glass to the interior walls of the courtyard plan improves the performance under both clear and overcast sky conditions and provides the best equity of exposure across all four design variants.

Circadian daylight potential and electric lighting demand

Increasing access to daylight by adding more transparency between spaces can boost circadian potential across a population of users who spend time moving throughout a building interior over time. As occupants spend a large amount of time away from their desks during the workday, a dyamic approach to evaluating their position is needed. This final section reveals the percentage of time (daily hours from 8am-5pm) that each occupant meets the 150 EML threshold from daylight. This value will be referred to as Circadian Daylight Potential and can help articulate the inequities between building occupants based on their class (Figure 4). In contrast to what was presented in Figure 3, this representation includes data from across the 8am – 5pm workday and moves beyond the WELL recommendation. We can think about each of these profiles as having a different degree of access to daylight based on their seated workspace positon and where activities take them throughout the day. The more access they have to daylight throughout the day, the higher their potential to meet circadian exposure recommendations.

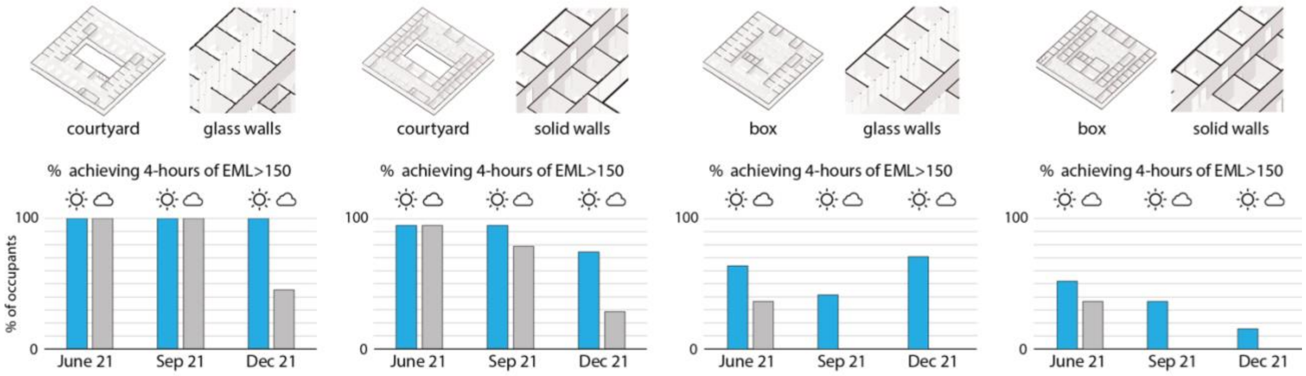

Figure 3: shows the % of occupants that achieve the WELL 150 EML threshold using a weighted approach under clear (blue) and overcast (grey) skies. Each of the 10 profiles described in Figure 1 are associate with a class of similar occupants. To compute this, the performance of each typological profile is multiplied by the number of similar occupants in that class. This approximates performance for the full population of occupants in each building.

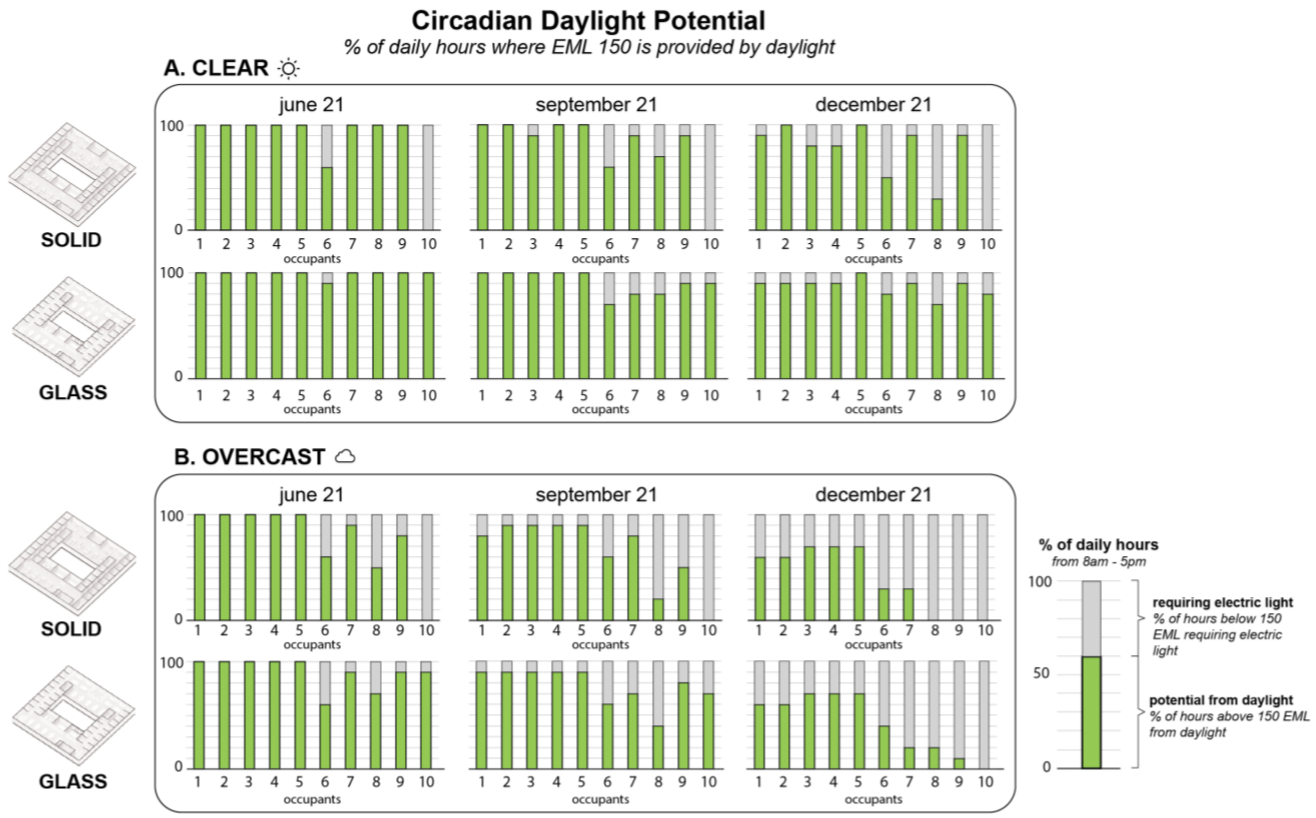

Figure 4: shows stacked bars for the % daily hours where EML 150 is met by daylight (in green) stacked below the % that would require supplemental electric light (grey) in the courtyard variant. Results for clear skies are shown in A) and overcast skies shown in B). This simple graphic illustrates the percentage of time that each occupant would meet their circadian needs from daylight and begins to illustrate the light inequity experienced by those occupants who spend more time in light-deprived zones within the courtyard building.

Lacking exposure to daylight during any portion of the day may result in deficiencies over time. These occupants would be almost exclusively reliant on electric light sources, which as Safranek et al., 2023 discuss, often fall short of meeting the recommended EML target at eye-level. Figure 4 attempts to illustrate that concept by breaking down the percentage of time when an occupant's eye-level EML exposure exceeded 150 EML from daylight as they moved through the courtyard typology over time. We can see a difference in the percentage of time when electric light would be needed to help supplement deficient timesteps under clear and overcast sky conditions, but we can also see the impact of glass interior partitions on some of those profiles. Occupant 10 showed the biggest improvement, but increases can also be seen for occupants 6-10, representing the performance of more than half the occupants in this building. Under overcast sky conditions in both glass and opaque design conditions, occupants 6-10 would need to rely on electric lighting for some portion of the time.

Conclusion

The findings presented in this paper are meant to illustrate the impact of building form, interior material, and typical occupancy scenarios on non-visual health potential across a dynamic occupant population. The authors have introduced a method of integrating dynamic occupant behavior to evaluate whether daylight can meet adequate light exposure recommendations across a population of occupants. While this paper relied on 3 annual and 10 hourly timesteps to illustrate performance under two sky conditions, future work is needed to expand this analysis to an annual climate-driven timeseries. This would help contextualize the performance of any given building within its climate and account for daylight availability across the year.

The use of a weighted scoring system allows us to define a sample of occupant behavior profiles and use it to predict the performance for a larger population of occupants. While this approach is simple and fast for building designers, it lacks a high degree of accuracy and does not capture the range of possible outcomes that would be possible given a more stochastic approach. To improve upon this, we are looking into agent-based computation to generate more stochastic behavioral profiles and evaluate performance as a probability rather than a singular result.

The authors are also working on a forthcoming publication to integrate electric light sources and operated shading systems into this workflow and test control scenarios to predict energy savings over time. This work is a critical building block to expand our evaluation of occupant light exposure across space and over time.

Future work is needed to apply this workflow to a larger catalog of building forms and electric lighting solutions and establish a baseline of performance for non-visual health potential. This will help designers contextualize the impact of design decisions on circadian daylight potential and electric lighting demand. In its current version, WELL v2 Feature L03 recommends a minimum EML (or m-EDI (D65) exposure at eye-level for seated work stations, but does not consider other spaces in the building where occupants spend time. Portable laptops and smart phones have liberated many office workers from their desks, allowing them the flexibility to work in different spaces. By not including meeting and social spaces in our evaluation of eye-level light exposure, we cannot accurately calculate the daily light dose of building occupants.

This paper reveals the importance of including dynamic behavior in the evaluation of eye-level light exposure, as occupants move thoughout the day and may experience deficiencies (or benefits) in daily exposure when spending substantial time away from their desk. Furthermore, it illustrates the impact of integrating daylight into social spaces (coffee stations and break rooms) where people spend time in the mornings. This could improve non-visual and social health across a population of occupants.

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