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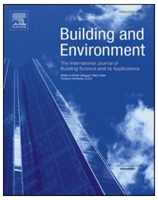

The value of daylight in office spaces

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ABSTRACT

The presence of natural light in indoor spaces improves human health, well-being, and productivity, particularly in workplace environments. Do the social benefits of daylight translate into economic value as measured by what office tenants are willing to pay? Using a sample of 5154 office spaces in Manhattan, we pair urban daylight simulation with a hedonic valuation model to determine the marginal value of daylight in offices. Holding all other factors constant, we find that occupied spaces with access to high amounts of daylight (as measured by 55% spatial daylight autonomy) have a 5–6% value premium over occupied spaces with low amounts of daylight (as measured by less than 55% spatial daylight autonomy). We simulate the distribution of daylight on each office floor individually, taking into account architectural and location-specific characteristics. Then, using the hedonic model, we determine the added value of daylight in the office spaces. The results show, for the first time, that an estimated 74% of office spaces throughout Manhattan have low daylight, and that in a dense urban environment with differentiation in daylight levels, tenants value high daylight. Daylight value is independent of other building, neighborhood, and contract characteristics. By revealing the added value of daylight in commercial office spaces, we suggest that daylight is a key design driver and thus, should be considered in design, policy, planning, and project financing.

1. Introduction

Daylight has a positive impact on human well-being. Insofar as environmental conditions affect human health, access to natural daylight benefits people, both physiologically and psychologically. A wide body of literature shows that, particularly in workplaces, natural light leads to greater workplace productivity, decreased stress, and higher employee satisfaction [1–4]. Given that working adults across cultures spend the majority of their time indoors [5–9]; it is critical that we optimize the conditions of work spaces—improving indoor environmental factors such as acoustics, air quality, and daylight—for inhabitant well-being.

Historically, daylight has been viewed not as an amenity but a right and necessity. Protecting access to daylight manifests in urban zoning policies throughout cities around the world. In the United Kingdom, the doctrine of ancient lights (dating back to 1663 and still in effect today) protects the access to light through an existing window [10]. In the United States, litigation and regulation in a number of states protect building occupants' right to light [11,12]. The urban form of many cities today are shaped by zoning policies enacted throughout the 20th Century that aim to protect both private and public rights to light [12]. Most notably, in New York City, the zoning regulations of 1916 and 1961 aimed to minimize shading and ensure that daylight reaches pedestrians on the street by stipulating rules about the exterior form of buildings [13].

Given the human health benefits of daylight, as well as the energy saving potential of using natural light to reduce the electric lighting load [14]; daylight is considered to be a fundamental component of building sustainability. Most green building rating systems, such as the Leadership in Energy and Environmental Design (LEED) certification and the WELL Building Standard [15,16] reward buildings that have good daylight access.[1] Because of its positive impact on human health and

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[1] LEED and WELL are widely-used, tiered certification systems that reward sustainable design features that, when added up, provide an overall rating for the project.

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energy savings, indoor daylight contributes to the overall sustainability of buildings, from both an environmental and social standpoint.

The aforementioned urban zoning regulations and green building certifications indicate that, as a society, we value daylight in buildings. Does the social valuation of daylight translate economically? If, in fact, it does then the real estate market should indicate a willingness to pay for better daylight in a space. To our knowledge, there are no prior empirical studies that measure the value of daylight in the commercial office real estate market. In this work, we pair architectural building performance simulation with real estate financial econometrics to ask: In a dense urban setting where access to daylight is unevenly distributed, how much are tenants willing to pay for spaces with good daylight access?

2. Literature

Previous research has found that sustainable buildings command a financial premium over conventional properties in both rental and sales transactions in cities around the world. This trend is true in residential and commercial markets, though notably more pronounced in the latter [17]. Studies on commercial properties in the United States, United Kingdom, Switzerland, and the Netherlands have identified a 13–30% premium on sales transaction prices and a cash flow increase of 6.5–21.5% in rental properties [18–23]. These studies have primarily evaluated the sustainability of buildings based on green building certification systems, such as LEED. Less work has been done to evaluate the economic incentive of individual design measures that contribute to the overall sustainability of buildings. Studies that do evaluate individual sustainability measures have considered energy efficiency, walkability and transportation access [22,24,25]. Most similar to the work in this paper, Fleming et al. evaluated the real estate value of direct sunlight exposure for residential properties in New Zealand [26]. They measured the amount of direct sunlight reaching the roof of each building. No previous studies, to our knowledge, have quantified the impact of daylight performance on rent prices in the commercial office market; nor have previous studies measured the value of daylight distribution on specific floors of a building.

3. Material and methods

To identify the economic impact of natural daylight on real estate value, we measure the differences in rent between office spaces that have high daylight access and those with low daylight access. We test whether office spaces with more daylight will have a financial value differential over those with low access. First, we model daylight distribution in 5154 commercial office spaces in Manhattan in New York City. Then, we input the daylight simulation results into a hedonic pricing model, a multiple regression that identifies the impact of each independent variable on the dependent variable, in this case, rent price. Inputting the daylight results along with other building, neighborhood, and location-based characteristics we identify the marginal value of daylight in the office rental prices, holding all other factors constant. The contributions of this work are two-fold: first, presenting a city-wide assessment of spatially-distributed daylight performance in office spaces in Manhattan; and second, identifying the value of daylight in the rental prices of these office spaces.

3.1. City-wide spatially distributed daylighting simulations

In dense urban environments, the daylight penetrating into a building depends largely on the shape of the floor plate, façade elements, neighboring buildings, size of the street blocks, and width of urban canyons [27]. Daylight modeling simulates how natural light permeates through an indoor space, taking into account the surrounding context and physical characteristics of the interior. We simulate daylight entering each floor throughout Manhattan individually. While running simulations with this resolution is simple for a single space, it is a computational challenge for a city-wide sample set. Limitations in both computational power and the ray-tracing method require that we develop a new work flow to model each floor individually for all of the

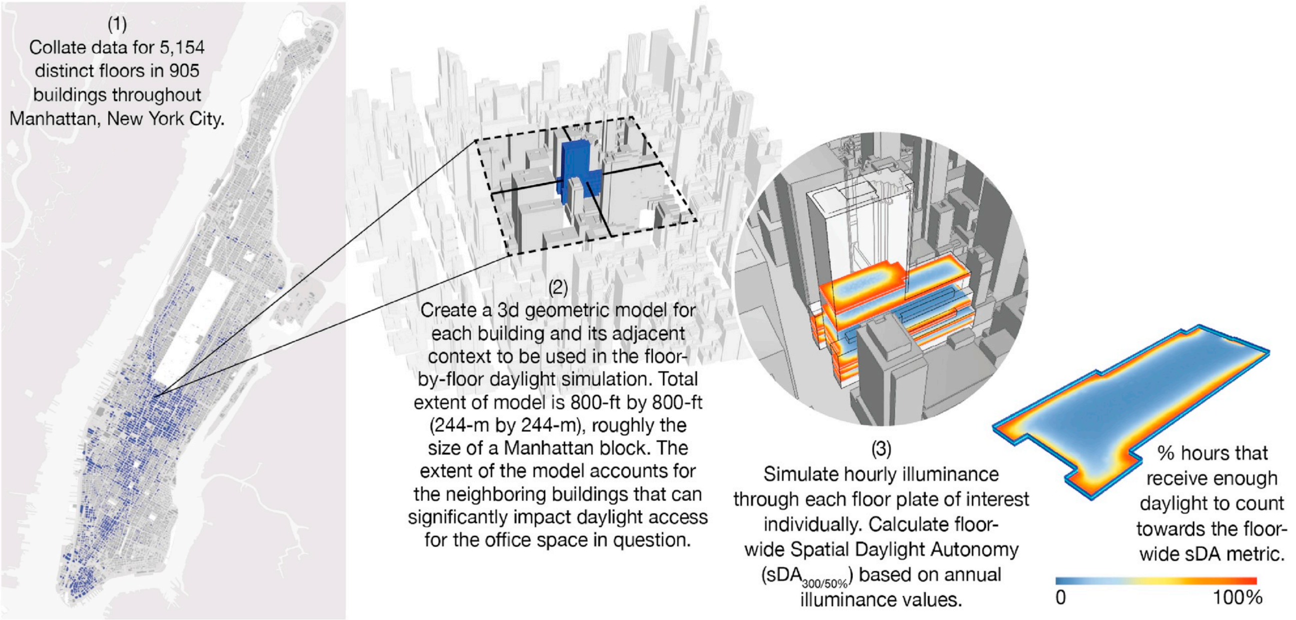

Fig. 1. City-scale Floor-by-floor Daylight Simulation Work Flow

Notes: Buildings of interest from the NYC DoITT 3D Model are identified using CompStak's rent transaction data. For each of these buildings, we isolate it with its surrounding context to create a Radiance model in order to perform the daylight simulation. This model contains each individual floor of the building that corresponds to a lease contract observation in CompStak's data, and the simulation calculates the illuminance throughout the floor plate for each hour of the year. Using the illuminance values, we calculate the spatial daylight autonomy, an annual metric on a scale of 0–100% that indicates how much of the floor area receives adequate daylight for a portion of occupied hours.

Table 1
Summary Statistics for variables included in the hedonic model. Mean and standard deviation presented for all observations, and separately for the low (0–55% sDA), high (55–75%), and very high (75–100%) daylit spaces.

Dependent Variables		All Observations		Low (sDA 0–55%)		High (sDA 55–75%)		Very High (sDA 75–100%)	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Net Effective Rent ($ per sq.ft.)		49.944	(20.551)	47.324	(18.416)	56.059	(25.532)	57.901	(21.632)
Log Net Effective Rent		3.839	(0.376)	3.792	(0.358)	3.941	(0.402)	3.990	(0.377)
Variable of Interest									
Spatial Daylight Autonomy ($sDA_{300/50\%}$)	Low (0–55%)	0.724	(0.447)	–	–	–	–	–	–
	High (55–75%)	0.161	(0.367)	–	–	–	–	–	–
	Very High (75–100%)	0.115	(0.319)	–	–	–	–	–	–
Building Characteristics for Each Contract									
Building Class	A	0.545	(0.498)	0.507	(0.500)	0.633	(0.482)	0.661	(0.474)
	B	0.383	(0.486)	0.411	(0.492)	0.325	(0.469)	0.290	(0.454)
	C	0.072	(0.258)	0.082	(0.275)	0.042	(0.200)	0.049	(0.215)
–									
Building Age at Lease Signing (years)		67.766	(29.284)	69.763	(29.752)	61.813	(27.985)	63.514	(26.399)
Renovated building (1 = yes)		0.500	(0.500)	0.499	(0.500)	0.506	(0.500)	0.497	(0.500)
LEED Certified (1 = yes)		0.121	(0.326)	0.130	(0.336)	0.133	(0.340)	0.050	(0.218)
Fiber Lit Building (1 = yes)		0.950	(0.219)	0.943	(0.232)	0.962	(0.191)	0.974	(0.160)
Lease Contract Terms									
Transaction Floor Number	0–15	0.620	(0.485)	0.760	(0.427)	0.327	(0.469)	0.147	(0.355)
	16–30	0.276	(0.447)	0.179	(0.383)	0.511	(0.500)	0.562	(0.496)
	31–45	0.091	(0.287)	0.054	(0.226)	0.148	(0.355)	0.244	(0.430)
	46 and over	0.013	(0.113)	0.007	(0.086)	0.014	(0.117)	0.046	(0.209)
–									
Lease Duration (years)	5 or less	0.393	(0.488)	0.387	(0.487)	0.391	(0.488)	0.435	(0.496)
	6–10	0.423	(0.494)	0.391	(0.488)	0.512	(0.500)	0.501	(0.500)
	11–15	0.135	(0.342)	0.160	(0.367)	0.081	(0.274)	0.057	(0.232)
	16–20	0.036	(0.186)	0.046	(0.209)	0.014	(0.117)	0.007	(0.083)
	21–25	0.007	(0.084)	0.010	(0.099)	0.000	(0.000)	0.000	(0.000)
	26 or more	0.005	(0.070)	0.006	(0.080)	0.002	(0.045)	0.000	(0.000)
–									
Free Rent Period (months)	No free rent	0.184	(0.387)	0.187	(0.390)	0.174	(0.379)	0.174	(0.379)
	6 months or less free	0.546	(0.498)	0.512	(0.500)	0.610	(0.488)	0.669	(0.471)
	7–12 months free	0.228	(0.419)	0.246	(0.431)	0.204	(0.403)	0.144	(0.352)
	13–18 months free	0.035	(0.184)	0.045	(0.207)	0.010	(0.099)	0.010	(0.098)
	19–24 months free	0.005	(0.068)	0.006	(0.075)	0.001	(0.031)	0.003	(0.053)
	Over 24 months free	0.003	(0.054)	0.004	(0.061)	0.001	(0.031)	0.000	(0.000)
–									
Landlord Concession (Work Type)	As-Is	0.016	(0.127)	0.017	(0.131)	0.009	(0.094)	0.021	(0.143)
	Built to Suit	0.001	(0.025)	0.001	(0.026)	0.000	(0.000)	0.001	(0.037)
	New Building Installation	0.044	(0.206)	0.040	(0.196)	0.052	(0.221)	0.061	(0.240)
	Not Specified	0.140	(0.347)	0.131	(0.338)	0.155	(0.362)	0.174	(0.379)
	Other	0.001	(0.025)	0.000	(0.021)	0.002	(0.045)	0.000	(0.000)
	Paint & Carpet	0.002	(0.042)	0.002	(0.039)	0.002	(0.045)	0.003	(0.053)
	Pre-Built	0.023	(0.149)	0.018	(0.133)	0.033	(0.178)	0.039	(0.193)
	Tenant Improvements	0.770	(0.421)	0.788	(0.408)	0.741	(0.438)	0.696	(0.460)
	Turnkey	0.003	(0.058)	0.002	(0.047)	0.007	(0.083)	0.006	(0.074)
–									
Sublease (1 = yes)		0.118	(0.323)	0.128	(0.334)	0.101	(0.302)	0.079	(0.270)
Partial Floor Flag (1 = yes)		0.523	(0.500)	0.524	(0.499)	0.551	(0.498)	0.479	(0.500)
Multiple Floors in Lease (1 = yes)		0.237	(0.426)	0.269	(0.443)	0.174	(0.379)	0.129	(0.336)
Tenant Broker (1 = yes)		0.628	(0.483)	0.643	(0.479)	0.595	(0.491)	0.578	(0.494)
Landlord Broker (1 = yes)		0.682	(0.466)	0.686	(0.464)	0.685	(0.465)	0.653	(0.476)
Number of Observations		6267		4539		1008		720	

spaces throughout the city.

Previous urban daylight simulation methods have simplified the urban-scale model in various ways to account for the computational limitations. Compagnon proposed an early method for urban daylight simulation that calculates the irradiance on the facades [28]. This widely used approach predicts how much sunlight falls on the external faces of the buildings. It does not consider, however, what happens to the light as it moves from outside to inside. Urban Daylight, developed by Dogan et al. expands upon this method by modeling the facade irradiance values and then interpolating how the light will be distributed within the space [29]. While this approach drastically reduces the computation time required to do spatially-distributed daylight simulations, it assumes all daylight entering the building to be diffuse and does not consider direct daylight penetration. In this study, we are interested in knowing how much direct and diffuse daylight penetrates throughout the full floor plate. Rather than interpolating the light distribution in the space, we simulate the hourly illuminance values at each point in the analysis grid, both to account for direct and diffuse light, and to ensure precision and confidence in the results at each point. Thus, this work is significant in both the scale of the urban daylight simulation study and also in the use of the daylight performance results to determine the added value of a qualitative architectural feature via the hedonic pricing framework. The spatial distribution of the sample within Manhattan, and a description of the modeling approach are illustrated in

Fig. 1.

Given the computational intensity of simulating spatially-distributed daylight for floors throughout a city, we break down the full Manhattan model into a series of smaller models specific to each building in the sample set. Each model is sized to include the building and its surrounding context. The result is an 800-foot-by-800-foot (244-m-by-244-m) square model scene with the building of interest at the center. The total extent of each model is slightly larger than a standard New York City block, sized to include neighboring buildings that would have a notable effect on the internal daylight distribution [30]. We further subdivide the building model into floor plates of interest and assign a 6-foot-by-6-foot (1.8-m-by-1.8-m) grid of sensor points throughout each floor plate at a height of 2.5 feet (0.76 m) from the floor. We assume a 30% window-to-wall ratio and 11.4 foot (3.5 m) floor-to-ceiling height for all spaces. The models do not include internal partitions, furniture, core spaces, or window treatments such as blinds. This is a limitation of the input data and modeling approach. However, most rented office spaces are fit-out by the tenant once they move in, and often the internal layout is modified during the fit-out. Assuming that the tenant will change the space once they occupy the floor, the model estimates the total possible daylight that the space receives considering the external context and floor plate shape. In other words, the simulations estimate the total *potential* daylight in the space.

To model daylight autonomy, we first simulate illuminance (the total amount of direct and diffuse light) falling onto a given surface at one point in time. This is calculated throughout every floor plate in our sample for all 8760 h of the year. We model daylight using the climate-based backward ray-tracing programs Radiance (version 5.0), DAYSIM (version 4.0), and DIVA (version 4.0), taking into account both the sun and sky conditions at the particular location [31–34]. Using these results, we calculate the floor's spatial daylight autonomy (sDA), a metric that measures the percentage of the floor area that receives a sufficient amount of ambient natural light. Qualitatively, sDA is a measure that describes the extent to which a space is naturally illuminated. The threshold for sufficiency, as defined by the Illuminating Engineering Society of North America (IESNA), is 300 lux for 50% for all occupied hours ($\text{sDA}_{300/50\%}$). We assume the occupied hours to be standard office work hours from 8am to 6pm, Monday through Friday. The $\text{sDA}_{300/50\%}$ threshold is referenced in both the LEED and WELL building certification systems [15,16,35], and considered a best practice throughout the industry.

For each office floor in question we run the following Radiance programs to obtain the hourly illuminance level at each sensor point within analysis grid: radfiles2daysim, gen_dc, ds_illum, and ds_el_lighting [32,34]. The Radiance simulation parameters used are: ambient bounce (ab) 5, ambient division (ad) 512, ambient super samples (as) 20, ambient resolution (ar) 300, ambient accuracy (aa) 0.1, limit reflections (lr) 6, specular threshold (st) 0.1500, specular jitter (sj) 1.0000, limit weight (lw) 0.001953125, source jitter (dj) 0.0000, source substructuring (ds) 0.200, direct relays (dr) 2, direct pretest density (dp) 512, direct thresholding (dt) 0. We assume the following material reflectance values for various building components: walls – 50%, floor – 20%, ceiling – 70%, exterior facades – 30%, ground – 20%, windows – 96% reflectance with 88% transmittance. We specify a transmittance value corresponding to that of a single pane window to measure the total potential light entering the space. As described earlier in this section, in the simulations, our objective is to measure the upper bound of daylight access. This value may be less depending on the specific glazing properties, shading elements, and interior design elements.

We use the sDA metric as an indicator of total daylight potential in a space, particularly with the aim of comparing properties within a dense urban context. We recognize that, although we employ the sDA metric as it is defined by IESNA, we do not follow certain widely-used IES LM-83-12 and LEED criteria—namely, using a 2-foot-by-2-foot grid spacing and consideration of dynamic shading systems [15,35]. In this work, we employ a 6-foot-by-6-foot (1.8-m-by-1.8-m) grid, as we are not simulating to measure LEED compliance. We chose the grid spacing to match the resolution of the geometric model and interior floor layouts, and to enable the urban scale computation of many spaces at once.[2] Moreover, we do not consider the core inside floor plates, assume open floor plans, and simplify the building facade properties. Particularly disregarding the core inside a floor may cause an underestimation of sDA results. Our primary objective in the simulations, however, is to assess the impacts of floor plate shape and surrounding context on daylight accessibility in a dense urban setting. To this end, the specified modeling parameters provide an adequate estimate.

In this work, our aim is to measure how much *potential* daylight might enter an office, considering mainly the shape of the building, height of the floor, and the neighboring context. To this end, we believe that sDA is a valid and reliable metric despite its limitations. We acknowledge that sDA is not a holistic indicator of daylight quality and comfort in a space. It measures minimum illuminance levels throughout the day, ensuring primarily that spaces are not underlit. It does not consider daylight quality, overlighting, or visual discomfort. Our objective in this work, however, is not to capture the full qualitative visual experience within an office. This depends significantly on the architecture, facade system, internal layout, and material properties of the space. In this work, sDA serves as a simplified measure of comparing daylight access in office spaces across a city; we suggest that quality and comfort are considered in a subsequent study to further investigate daylight conditions throughout the urban environment.

3.2. Hedonic pricing model analysis

To analyze the relationship between daylight performance and effective rent observed in lease contracts, we employ a hedonic pricing model [36]. Hedonic pricing theory measures the value of differentiated products, considering the utility derived for the tenant by building, contractual, temporal, and neighborhood characteristics [18,19,37–39]. In short, the hedonic framework assumes that individual building components independently add to the overall rent price [36]. Equation (1) presents the functional form of the vectorized hedonic model specification:

$$Y = \alpha + \varphi D_i + \beta B_i + \gamma L_i + \delta N_i + \omega T_i + \varepsilon_i, \tag{1}$$

where the dependent variable Y is the logarithm of the realized net effective rent per square foot for rental contract observation i. D is the variable of interest, the categorical daylight autonomy level ($\text{sDA}_{300/50\%}$ 0–55%, 55–75%, 75–100%) for rental contract observation i. B is a vector of exogenous hedonic building characteristics (such as age, class, LEED certification, etc.) of the building in which the rental contract observation i is located. L is a vector of the lease contract terms (such as lease duration, transaction floor number, landlord concessions, etc.) for rental contract observation i. N is a vector of exogenous location fixed effects by Manhattan neighborhood, defined by 24 submarkets (such as Chelsea, Financial District, Grand Central, and Times Square) listed in Table A2 in the Appendix. T is a vector of time fixed effects by quarter and year that the lease is executed, between 2010 and 2016. φ, β, γ, δ, and ω are the estimated parameter vectors, representing the functional relationship between each independent variable and the dependent variable. ε is the error term, a vector of independent, identically distributed regression disturbances. All variables are outlined in Table A2 in the Appendix.

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[2] It is worth nothing that the larger grid resolution has limited effect on the results. We have tested our model set-up against a 2-foot-by-2-foot grid and find that the 6-foot-by-6-foot tends to inflate the sDA results marginally. The impact is most notable in low daylight spaces where the sDA results are increased by maximum 2%; in high daylight spaces the impact on sDA values is less than 1%. Given the resolution of our simulations, the maximum 2% variation falls within the margin of error for the sDA results.

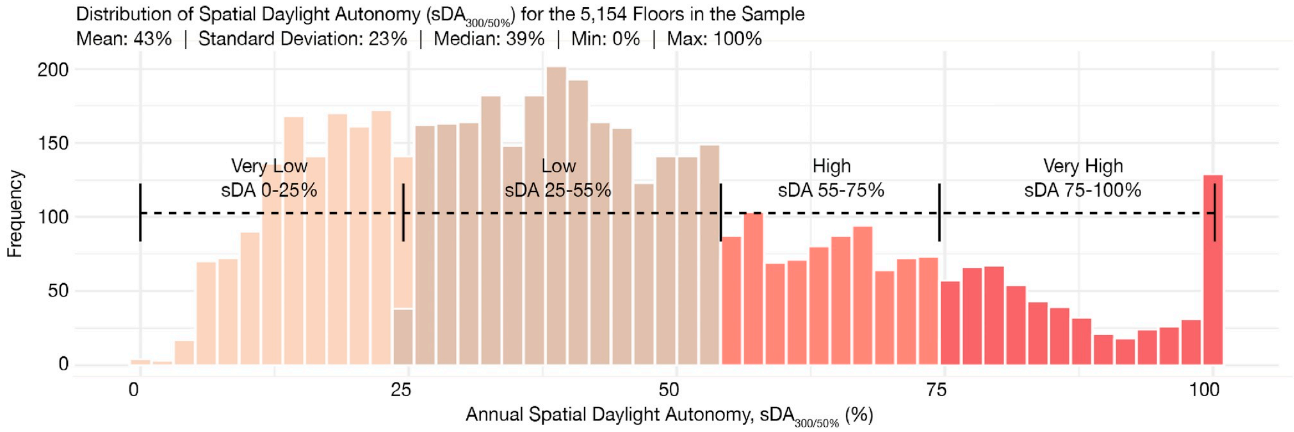

Fig. 2. Distribution of daylight simulation results for the 5154 spaces modeled.
Note: The color coding indicates the sDA thresholds of 25%, 55% and 75% to illustrate how daylight performance varies within the sample. 74% of the spaces have very low to low daylight levels (0–55% sDA), and 26% of the spaces have hight to very high daylight levels (55–100% sDA). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.3. Data

In total, we analyze the spaces associated with 6267 lease contracts signed between 2010 and 2016, located on 5154 floors throughout Manhattan.[3] We use multiple data sources to gather information about the office spaces in the sample: a city-wide three-dimensional Level of Detail 1 to 2 model from New York City's Department of Information Technology and Telecommunications; property information from the city's Department of Planning; rental contract data from CompStak; sustainable building certifications from Green Building Information Gateway; and telecommunications data from Geotel [30,40–43]. Table A1in the Appendix describes all data sources used.[4]

Table 1 provides the descriptive statistics (mean and standard deviation) of the lease contract data for the sample set as a whole, and separately for each sub-sample of daylight low, high and very high daylight values. Table A2 in the Appendix provides a description of each variable included in the data.

The variable of interest is spatial daylight autonomy (sDA$_{300/50\%}$). For each contract-floor, the variable of interest sDA$_{300/50\%}$ is a value between 0 and 100%. We separate the results into three categories: *low daylight* (0–55% sDA$_{300/50\%}$), *high daylight* (55–75% sDA$_{300/50\%}$), and *very high daylight* (75–100% sDA$_{300/50\%}$). Henceforth, we refer to these categories using the terms low daylight, high daylight, and very high daylight; or alternatively, low sDA, high sDA, and very high sDA. The ranges are based on the LEED recommended 55% and 75% thresholds for good daylight autonomy in commercial office spaces [15]. We adopt these thresholds because they are widely applied and understood within the building sector, and currently guide the daylighting design of contemporary buildings. Seventy-two percent of contracts in our sample are in spaces with 0–55% sDA$_{300/50\%}$, putting them in the low daylight category. The average sDA$_{300/50\%}$ for these spaces is 31.4%. Only 28% of contracts have high daylight to very high daylight, and for these spaces the average sDA$_{300/50\%}$ is 64.2% and 87.4%, respectively.

To measure value, we use the net effective rent in U.S. Dollars. CompStak defines net effective rent as the "actual amount of rent paid (subtract[ing] lease concessions from starting rent)" [40]. We use the logarithmic transformation of the dependent variable in the regression, as it enables a clear interpretation of the resulting coefficients and it adjusts for slight skewness of the rent price distribution. The average net effective rent is $49.94, with a standard deviation of about $20.55 per square foot (or in metric units, $537.55, with standard deviation of $221.20 per square meter). In Table 1, in addition to presenting descriptive statistics for the full sample set as one, we divide the sample by the daylight levels to explore the statistics for each group. Low daylight contracts have an average net effective rent of $47.32 per square foot ($509.35 per square meter) with comparable variation to the whole sample. High daylight and very high daylight achieve average net effective rents of $56.05 and $57.90 per square foot ($603.32 and $623.23 per square meter), respectively, with comparable variation. Notably, these values are approximately $8.00 to $10.00 more per square foot that the average rent in the low daylight category. This is not indicative of the overall premium, rather it is an observation of the data statistics within each daylight performance group.

For controls, we add the building class associated with each contract, the building's age, renovation status, LEED certification, and whether the building has fiber-optic telecommunications. When we differentiate between low, high, and very daylight we find that contracts with high and very daylight cluster in class A more than those with low daylight, 63% and 66% versus 50% of low daylit spaces. The building age is on average 70 years, 62 years, and 64 years for low, high, and very high daylit spaces, respectively. LEED certification occurs 13%, 13%, and 5% for the low, high, and very high daylit samples, respectively. Lastly, fiber optic infrastructure is nearly standard with at least 94% of spaces across all groups being in a fiber lit building (i.e., in a building connected to a high-speed fiber optic cable).

In addition, we control for lease contract characteristics. Again, when differentiating between low, high, and very high daylight, we see that lease contract terms vary. Transaction floors for high and very high daylit spaces cluster between floors 16–30, and lease durations are more frequently 6–10 years. Across all three groups rent free periods are generally for six months or less, and landlord concessions are generally in cash through tenant improvements. Finally, subletting, partial floor leasing, multiple floor leasing, tenant brokerage and landlord brokerage is comparable across all of the samples.

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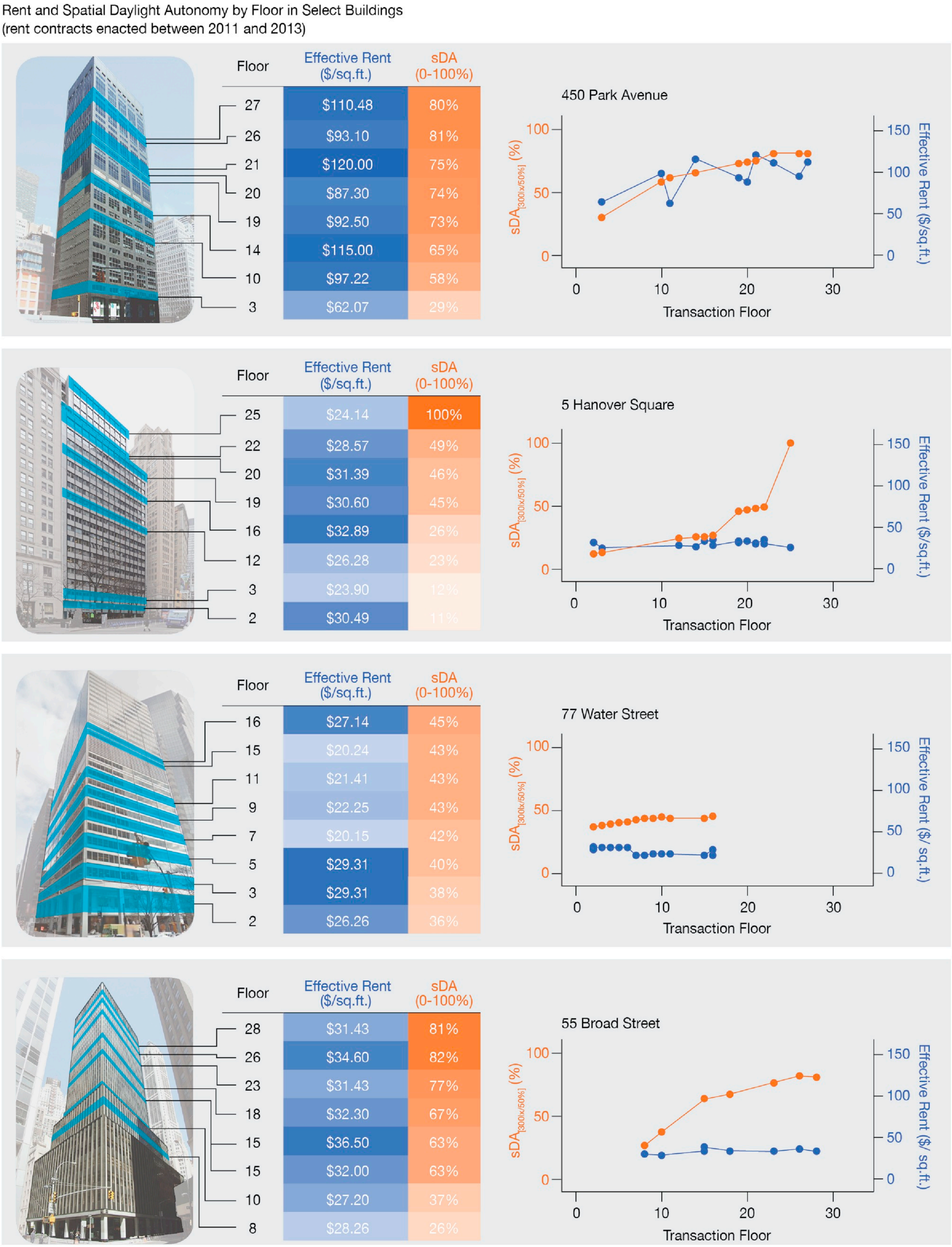
[3] The total number of contracted spaces differs from the floor count because of particular terms in the contracts. Some of the floors in the sample are associated with multiple contracts, either because there are multiple tenants sharing one floor or the space changed hands within the 2010 to 2016 period. Inversely, some contracts encompass more than one floor, as the tenant leased multiple floors together.

[4] Data from the NYC DOITT, NYC Department of Planning, and GBIG are public and open access through their respective online portals. CompStak and Geotel data sets are proprietary. The data are based on market research and, therefore by nature, are privately held.



Rent and Spatial Daylight Autonomy by Floor in Select Buildings
(rent contracts enacted between 2011 and 2013)

450 Park Avenue

Floor	Effective Rent ($/sq.ft.)	sDA (0-100%)
27	$110.48	80%
26	$93.10	81%
21	$120.00	75%
20	$87.30	74%
19	$92.50	73%
14	$115.00	65%
10	$97.22	58%
3	$62.07	29%

5 Hanover Square

Floor	Effective Rent ($/sq.ft.)	sDA (0-100%)
25	$24.14	100%
22	$28.57	49%
20	$31.39	46%
19	$30.60	45%
16	$32.89	26%
12	$26.28	23%
3	$23.90	12%
2	$30.49	11%

77 Water Street

Floor	Effective Rent ($/sq.ft.)	sDA (0-100%)
16	$27.14	45%
15	$20.24	43%
11	$21.41	43%
9	$22.25	43%
7	$20.15	42%
5	$29.31	40%
3	$29.31	38%
2	$26.26	36%

55 Broad Street

Floor	Effective Rent ($/sq.ft.)	sDA (0-100%)
28	$31.43	81%
26	$34.60	82%
23	$31.43	77%
18	$32.30	67%
15	$36.50	63%
15	$32.00	63%
10	$27.20	37%
8	$28.26	26%

Fig. 3. Spatial daylight autonomy and rent prices on sample floors in select buildings.
Note: The floors on which we simulated daylight are highlighted in blue on the building images. The tables and charts list the transacted rent price and daylight results for each floor. It includes only rent contracts signed between 2011 and 2013. In the case of 55 Broad Street, there are two rent prices listed for floor 15 because the floor is shared between two tenants who have independent rent contracts. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2

Full hedonic pricing model regression daylight results (dependent variable: Logarithm of effective rent per square foot ($/sq.ft.)).

Variables	(1)	(2)	(3)	(4)	(5)
Variable of Interest: Spatial Daylight Autonomy (Base Level: Low Daylight (sDA 0–55%)					
High Daylight	**0.108*****	**0.101*****	**0.089*****	**0.035*****	**0.050*****
(sDA 55–75%)	[0.011]	[0.010]	[0.009]	[0.010]	[0.014]
Very High Daylight	**0.122*****	**0.103*****	**0.104*****	**0.018**	**0.061****
(sDA 75–100%)	[0.013]	[0.011]	[0.011]	[0.012]	[0.027]
Building Class (Base Level: Class A)					
Class B Building			−0.146***	−0.112***	−0.115***
			[0.010]	[0.010]	[0.010]
Class C Building			−0.236***	−0.198***	−0.202***
			[0.016]	[0.016]	[0.017]
Building Age at Lease Signing (years)			−0.010***	−0.010***	−0.010***
			[0.001]	[0.001]	[0.001]
Building Age, Squared			0.000***	0.000***	0.000***
			[0.000]	[0.000]	[0.000]
Renovated Building (1 = Yes)			0.041***	0.039***	0.040***
			[0.007]	[0.007]	[0.007]
LEED Certified (1 = Yes)			0.008	0.006	0.004
			[0.011]	[0.010]	[0.010]
Fiber-Lit Building (1 = Yes)			0.042***	0.021	0.023
			[0.016]	[0.016]	[0.016]
Lease Term Duration (Base Level: 6–10 years)					
Lease term 5 years or less				−0.045***	−0.045***
				[0.008]	[0.008]
Lease term 11–15 years				0.065***	0.064***
				[0.011]	[0.010]
Lease term 16–20 years				0.107***	0.106***
				[0.018]	[0.018]
Lease term 21–25 years				0.222***	0.220***
				[0.044]	[0.044]
Lease term 26 years or more				0.073	0.074
				[0.050]	[0.050]
*Free Rent Period (Base Level: 0–*6 months*)*					
No free rent				0.025***	0.025***
				[0.009]	[0.009]
7–12 months free				−0.033***	−0.033***
				[0.009]	[0.009]
13–18 months free				−0.043**	−0.044**
				[0.021]	[0.021]
19–24 months free				−0.118**	−0.130**
				[0.053]	[0.055]
Over 24 months free				−0.056*	−0.054*
				[0.029]	[0.029]
Sublease (1 = Yes)				−0.171***	−0.172***
				[0.011]	[0.011]
Partial Floor Flag (1 = Yes)				0.037***	0.036***
				[0.008]	[0.008]
Multiple Floors in Lease (1 = Yes)				0.018**	0.018*
				[0.009]	[0.009]
Tenant Broker (1 = Yes)				0.010	0.010
				[0.008]	[0.008]
Landlord Broker (1 = Yes)				0.037***	0.037***
				[0.009]	[0.009]
Landlord Concessions/Work Done (Base Level: Tenant Improvements)					
As-Is				0.041	0.041
				[0.029]	[0.029]
Built to Suit				−0.045	−0.044
				[0.070]	[0.068]
New Building Installation				0.063***	0.065***
				[0.012]	[0.012]
Not Specified				0.030***	0.031***
				[0.009]	[0.009]
Other				0.014	0.014
				[0.054]	[0.056]
Paint & Carpet				0.055	0.057
				[0.059]	[0.058]
Pre-Built				0.097***	0.099***
				[0.021]	[0.021]
Turnkey				0.141***	0.140***
				[0.040]	[0.040]
Transaction Floor Number (Base Level: Floors 0–15)					
Transaction Floor Number 16-30				0.116***	0.123***
				[0.009]	[0.010]
Transaction Floor Number 31-45				0.209***	0.223***
				[0.014]	[0.021]

(*continued on next page*)

Table 2 (*continued*)

Variables	(1)	(2)	(3)	(4)	(5)
Transaction Floor Number 46+				0.253***	0.316***
				[0.049]	[0.069]
Interaction Effect: sDA Level x Transaction Floor Number					
High sDA x Trans. Floor 16-30					−0.033
					[0.020]
High sDA x Trans. Floor 31-45					−0.027
					[0.033]
High sDA x Trans. Floor 46+					0.072
					[0.092]
Very High sDA x Trans. Floor 16-30					−0.043
					[0.031]
Very High sDA x Trans. Floor 31-45					−0.069*
					[0.038]
Very High sDA x Trans. Floor 46+					−0.228**
					[0.113]
Location Fixed Effects	Yes	Yes	Yes	Yes	Yes
Time Fixed Effects	–	Yes	Yes	Yes	Yes
Constant	3.838***	3.648***	3.993***	3.943***	3.936***
	[0.010]	[0.024]	[0.034]	[0.034]	[0.034]
Observations	6267	6267	6267	6267	6267
R-squared	0.315	0.448	0.536	0.600	0.601
F Adj R2	0.312	0.444	0.531	0.594	0.595

Notes: The five specifications presented: (1) includes location fixed effects; (2) adds time fixed effects; (3) adds the building characteristics; (4) adds contract lease terms; and (5) adds the interaction effect between sDA and floor number. Robust standard errors in brackets and statistical significance is denoted at the following levels ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

4. Results

4.1. *Daylight performance in offices*

A city-wide database of actual daylight levels on each floor of a building does not exist. To carry out this research, we created our own data of floor-by-floor daylight values. We simulate daylight distribution in 5154 office spaces, located in 905 buildings throughout Manhattan in New York City, as mapped in Fig. 1. To our knowledge, this is the first data set of floor-by-floor daylight autonomy values in buildings across a city.

In the LEED certification system, the requirements to earn the daylight the credits is 55% $sDA_{300/50\%}$ for the first tier, and 75% $sDA_{300/50\%}$ for the second tier [15]. We adopt these thresholds to organize the distributions of the daylight simulation results into three levels: low ($sDA_{300/50\%} < 55\%$), high ($55\% \leq sDA_{300/50\%} < 75\%$), and very high ($sDA_{300/50\%} < 75\%$). Fig. 2 depicts the distribution of daylight results across the sample. The average $sDA_{300/50\%}$ throughout the floors is 43%, with a standard deviation of 23%. The median $sDA_{300/50\%}$ is 39%. Sixteen percent of the floors have high daylight autonomy (i.e., $sDA_{300/50\%}$ between 55% and 75%) and 12% have very high daylight availability ($sDA_{300/50\%}$ over 75%). The median and mean sDA result are both less than the minimum 55% $sDA_{300/50\%}$ recommended by LEED. In total, 74% of the floors throughout this Manhattan sample have daylight autonomy levels below the LEED threshold.[5]

Fig. 3 depicts the spatial daylight autonomy results for floors within four buildings in the sample. Within each building, daylight autonomy increases as one moves from low to high floors. As indicated in these examples, there is a positive relationship between floor height and daylight performance. At higher elevations there are fewer surrounding buildings to shade the facade, allowing more sunlight to reach the windows. The correlation between daylight and floor number suggests that one of these variables may serve as a proxy for the other. The hedonic model, however, methodologically identifies the statistically significant impact of each variable on rent price independently. As shown in the charts in Fig. 3, the daylight level may increase with floor number, but the rent values do not always follow suit. The impact of both daylight and floor number on rent price is not clearly discernible from the sub-sample set alone. The hedonic model disentangles the impact of each factor on the dependent variable. We describe the method of separating daylight and floor number impacts using an interaction term in Section 4.2.

4.2. *Daylight valuation in offices*

To estimate the value of daylight, we operationalize a hedonic model that decomposes the value of buildings into their individual building and neighborhood characteristics. In this case, the effective rent price is a measure of value that a tenant is willing to exchange for a bundle of spatial characteristics they wish to lease. Thus, the effective rent is a measure of the weighted sum of the building characteristics, lease contract conditions, relative spatial market supply and demand as well as macro-economic market conditions. Table 2documents the results of the hedonic rent model specified in Equation (1). The results of the model explain up to 59.5% of the variation in net effective rent prices, in line with previous studies that use the same data [44,45]. The low daylight (0–55% $sDA_{300/50\%}$) level serves as the base category. We find that spaces with high daylight (55–75% $sDA_{300/50\%}$) have a 5.0% premium over spaces with low daylight, while spaces with very high daylight command a 6.1% premium over spaces with low daylight. This means that, for example, if the low daylight space transacts for $50 per square foot ($538.20 per square meter), the space with high daylight will transact for an added 5.0% or $52.50 per square foot ($565.11 per square meter), ceteris paribus. The premium expressed in the regression results approximates the difference in the average net effective rent values across the sDA categories, as depicted in Table 1 summary statistics.

To operationalize the model, we estimate via ordinary least squares with robust standard errors. We find that this form of the ordinary least squares model provides the best linear unbiased estimator of coefficients with heteroskedasticity-consistent robust standard errors [46]. For robustness, we estimated multiple specifications to assess the functional form of daylighting, the dependent variable, and the independent

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[5] Fig. 2 depicts a spike in observations at 100% $sDA_{300/50\%}$. This is a result of the sDA metric calculation approach. Some spaces receive much more than 300 lux for most hours of the day, while others just surpass the 300 lux limit. Despite the variation in daylight performance, they are all considered to have 100% $sDA_{300/50\%}$, and thus there is a accumulation of observations at the maximum level.

variables. Results are robust to these specifications, however the functional form of the model presented in the paper is selected for its ease of economic and statistical interpretation in application.[6] Furthermore, we employed a Double Selection Lasso technique, and found no change to our specification based on various penalization indicators. This procedure suggests that the model should include all co-variates to explain the variation of effective rents and the variable of interest sDA [47]. The five columns in Table 2 present the incremental development of the multiple linear regression model. In each column, a new set of variables is added in the following order: location fixed effects, time fixed effects, building characteristics, lease contract terms, and interaction effects. By building the regression incrementally, we are able to track how the variables interact with one another and impact the overall model fit.

In column (1), we add the variable of interest sDA and a neighborhood categorical variable to the model. For this specification, the model explains 31.2% of the variation of effective rent per square foot. Relative to the Grand Central neighborhood, we find that markets are generally less expensive with five exceptions: Columbus Circle, Madison/Fifth Avenue, Park Avenue, Sixth Avenue, and SoHo. These neighborhoods receive a relative value premium of 3.8%, 29.4%, 26.1%, 17.7%, and 6.5% more per square foot, respectively. The variable of interest sDA appears to be correlated with other factors at this stage, where relative to contracts with low sDA levels, high and very high contracts receive 10.8% and 12.2% more per square foot in effective rent.

In column (2), we add controls for macroeconomic conditions through a quarterly time categorical variable. For this specification, the model explains 44.4% of the variation of effective rent per square foot. The results indicate that effective rents positively increase quarter-over-quarter, and that relative to the first quarter of 2010, rents in the fourth quarter of 2016 are 48.8% higher for the Manhattan property market. The variable of interest sDA continues to have statistical significance and comparable scale in coefficient size, where relative to contracts with low sDA levels, high and very high sDA contracts receive 10.1% and 10.3% more per square foot in effective rent.

In column (3), we add controls for building characteristics: building class, building age, LEED certification, and fiber optic connectivity of the building. For this specification, the model explains 53.1% of the variation of effective rent per square foot. Relative to Class A buildings, Class B and C buildings receive effective rent per square foot discounts of −14.6% and −23.6%, respectively. Building age depicts comparable depreciation, where for every year that the building ages, the physical depreciation of the asset decreases the effective rent per square foot by −1.0%. For renovated buildings, effective rents per square foot are higher by 4.1%. Similarly, should a building have fiber-optic connectivity, there is an effective rent premium of 4.2%. LEED certified buildings, however, show no statistical significance and do not receive an effective rent premium in Manhattan. This is in line with previous research that shows that the marginal value of LEED certification decreases as the population of certified buildings increases in an area [18]. Finally, the variable of interest sDA continues to have statistical significance and marginally decreases in coefficient size, where relative to contracts with low sDA levels, high and very high contracts receive 8.9% and 10.4% more per square foot in effective rent.

In column (4), we add controls for leasing contract features: lease term, free-rent period, sublease clause, partial or multiple floor, brokerage, landlord concessions, and transaction floor number. For this specification, the model explains 59.4% of the variation of effective rent per square foot. Relative to a lease term of 6–10 years, effective rents per square foot are higher as the lease term increases up to a point. For example, leases that are 21–25 years long have an effective rent per square foot that are 22.2% higher. As rent-free periods increase, there is a decrease in effective rents per square foot, where contracts with 19–24 months free have the highest discounts of −11.8% less per square foot than 0–6 month leases on average. Contracts with subleasing clauses are discounted by −17.1%. In addition, partial and multiple floor contracts receive 3.7% and 1.8% more per square foot, respectively. Tenant concessions also play a key role in lease negotiations; results indicate that turnkey contracts yield the largest premium of 14.1%. Most notably, transaction floor number has strong statistical significance and marginally increases at floors higher in the building. Compared to contracts on floors 0–15, contracts on floors 16–30, 31–45, and 46 and above receive 11.6%, 20.9%, and 25.3% more per square foot in effective rent, respectively. The variable of interest sDA maintains significance at the high daylight level though it decreases to 3.5%. Very high daylight is not significant in this model. The addition of the lease terms, particularly transaction floor number, decreases the value associated with daylight levels. This is expected as daylight and floor number are closely tied. We address the relationship between the two variables in the next and final specification.

In column (5), we evaluate the interaction effect between floor number and the variable of interest sDA. The floors that are higher in a building transact for higher rent prices, as indicated in the results in column (4). This may be attributed to qualitative factors, such as greater prestige, better views, more acoustic separation from the street, and perhaps, increased daylight. As illustrated in Fig. 3, however, the relationship of daylight and floor number to rent value varies from one contract to another. Given the close relationship, it is important to determine whether floor number is serving as a proxy for sDA. To address this, we interact the floor number categories and the sDA categories to identify whether the sDA value premium is, in fact, associated with floor height or sDA [48]. The purpose of the interaction term is to identify how these two variables act together. By identifying the interaction effect, we determine how both sDA and floor number impact rent prices independently and in concert with one another.

To consider the condition of having both *high daylight and high floor number*, one must add the coefficients of both variables, plus the interaction term in line with the literature on interpreting conditional marginal effects [48]. The interaction effect is statistically significant only for very high sDA on floors 31–45 and floors 46 and above, with coefficients of −6.9% and −22.8%, respectively. The negative coefficient on the interaction terms indicates that the value of being on a high floor and having very high daylight is tempered. As none of the interaction terms for high sDA are statistically significant, the conditional value of a contract with high daylight at any floor level is simply the addition of the 5.0% sDA coefficient and the transaction floor coefficient. In the case of contracts with very high sDA, if they are in either floors 31–45 or 46 and above, there is a discount of either −6.9% or −22.8%, respectively. Thus, a contract with very high daylight on floor 46 or above has a conditional value of 6.1% for daylight performance plus 31.6% for transaction floor plus −22.8% for the interaction effect, resulting in a conditional premium of 14.9% more per square foot in net effective rent.

The interaction term measures the conditional value of daylight at specific floor heights. The results in the previous paragraph highlight that value that is associated with the conditional case of an office having *very high daylight on a high floor*. Because of the model specification, the interaction effect associated with very high daylight on a low floor is omitted and cannot be observed. Thus, to test the case of *very high daylight on a low floor*, we run a secondary specification of the hedonic model, changing the transaction floor base case to be floors 31 and over. The results of this analysis show that there is a deep discount of −23.4%

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[6] The low daylight (0–55%) is the base level in the regression. To validate the robustness of the model, we tested the $sDA_{300/50\%}$ as a continuous variable. The results of this test are consistent with the model's final function form. We choose to employ the categorical form of the variable in the final model for two reasons. First, the levels are consistent with the LEED daylight thresholds, 55% and 75%, which are accepted industry-wide as indicators of a well-lit daytime space. Second, occupants' perception of daylight levels can vary based on natural and electrical lighting conditions, as well as spatial conditions [50]; thus we choose to consider the daylight autonomy levels in steps that are clearly distinguishable rather than in single point increments.

associated with being on low floors (floors 0–15), along with a 9% value premium for the interaction between low floor and very high daylight. In other words, a *low floor with high daylight* has a 9% daylight premium (over the base case of a *high floor with low daylight*) but at the same time has a −23.4% discount because it is a low floor. Results of this analysis are available upon request. The statistical and economic discounts of being on lower floors overshadows the value that better daylight brings to the floor. This test shows that there is a value proposition associated with better daylight access on all floors, both high and low, however the discount of being a low floor outweighs the daylight premium.

5. Discussion

A century ago, the health benefits of daylight led to new urban zoning codes to ensure that pedestrians at street level would not be cast in perpetual shadow from the growing high-rise buildings [13]. The move signaled a societal appreciation of daylight as an amenity worthy of public rights, which translated into policy to ensure daylight for all. This work confirms that, today, this is still the case. The 5–6% financial premium for daylight in office rent prices indicates that people value natural light within indoor spaces. Its positive economic internalities and externalities (spanning from workplace productivity and office morale to occupant happiness and well-being) impact all facets of the built environment, including real estate, building codes, urban planning, and design. Most directly, the results can inform the pricing of properties in the real estate market, affecting both building owners and tenants. The financial premium may also be used to inform new building codes, as it did a century ago. Lastly, recognizing the market value of daylight can guide policies to ensure that all building inhabitants have equal access to adequate natural light regardless of economic means.

Daylight is a core consideration in architectural design. Buildings are oriented according to the sun's path, and facades are detailed in response to seasonal and daily conditions. In architectural practice, there are plenty of resources to design for better daylit spaces, from widely-used simulation tools to specialized lighting consultants. Thus, the quality and quantity of daylight in a space may be anticipated and shaped far before a new building is ever realized. When a project is being developed, daylight is sometimes a top priority and design driver, but other times it is not. It is for the latter cases that the results of this work are most important. In a situation where it is not prioritized, daylight-enhancing or daylight-controlling facade elements are more likely to be eliminated to potentially limit construction costs.[7] Understanding the importance of daylight design, not just in social and environmental but also in economics terms, can be the key to retaining daylight-optimizing design elements in a project. If a developer or investor knows daylight's value, then they can include it in the financial models to inform the budget of a project. Recognizing daylight's potential to increase the operating income can justify initial construction costs associated with creating better daylit spaces.

A large part of a property's value is associated with architectural characteristics that are not always quantifiable. When a potential tenant views an office space, more often than not, they are not basing their decision on measured daylight levels. To our knowledge, it is not standard practice to take illuminance measurements in a space, either by a broker or a potential tenant. Thus, tenants most likely assess the daylight quality based on their own *experience* in the space rather than any quantified indicator. This is a testament to the importance of spatial quality and individual occupant experience. The architectural elements that make a pleasant indoor space (such as layout, materials, daylight, and views) are often not considered in financial valuation. While it may not be standard to include spatial qualities in cash flow modeling, the tools to quantify such elements—either measured or modeled—are widely applied in design. Therefore, there exists an opportunity to incorporate building performance metrics, such as daylight levels, into financial valuation models at all stages of a building's development. For, once these features are understood in financial terms, they can be prioritized in the design and development process by all stakeholders, from architects to developers and building owners.

The hedonic model used in this work explains just under 60% of the rent price of office spaces in Manhattan, in line with previous studies [44,45]. Roughly 40% of the price, therefore, is still undetermined. This is not surprising as so much of real estate value depends on qualitative features of a space. Just as a tenant likely judges daylight through experience, architectural quality cannot be easily quantified in a real estate listing. Thus, it is important that we continue to develop new ways of characterizing spatial features so that their value can be recognized. One characteristic that is currently missing from the model is views. We predict that there exists a relationship between daylight and views, though in the current model, we do not distinguish between the two. Where there is a good view, there is often also high levels of daylight because both require a degree of spatial openness at the facade. Thus, it is possible that the variable of interest sDA may be serving a proxy for views, at least to a certain extent. However, this is not always the case and it is possible to also have daylight without preferential views and vice versa. This is an area for future research. If we are to better understand the value of architecture in economics terms, we need better analysis methods and metrics to evaluate views and other qualitative features.

While the results of this work directly applies to commercial offices in New York City, we expect them to be relevant for cities around the world. Previous work that compares commercial real estate in major cities globally finds that there are commonalities in the value trends associated with specific hedonic factors, such as size and building height [37]. We expect daylight to follow a similar relationship—the particular premium may differ but we expect there to be a consistent positive relationship between daylight and rent price. Given the widespread applicability of this work, we hope that it will lead to better daylight quality in office spaces in urban centers across the world.

6. Conclusion

Natural daylight has long been appreciated for its positive impacts on human health, energy efficiency, and spatial quality in buildings. While the benefits of daylight are widely acknowledged, until now, it has not been confirmed that the value is reflected in economic decision-making. We pair urban daylight simulation with real estate hedonic modeling to determine the value of daylight in the rental price of office spaces in Manhattan. We simulate the spatially-distributed daylight performance in 5154 floors in 905 buildings. We find that tenants pay 5–6% more for spaces with high daylight access over those with low daylight access. In other words, if a low daylight space transacts for $50 per square foot ($538.20 per square meter), the same space with high daylight will transact for an added 5.0% or $52.50 per square foot ($565.11 per square meter). This premium for daylight in the market is independent of all other factors, including LEED certification and floor number. The results further show that 74% of office floors in Manhattan receive low daylight. Thus, only a quarter of offices meet the minimum 55% $sDA_{300/50\%}$ threshold that is widely used as best practice within the building sector. The results indicate that, in a dense urban environment with differentiation in daylight levels, tenants value high daylight.

Given its integral role in the shaping of space, daylight has always been a critical factor in architectural design. It is not, however, often

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[7] There is no study, to our knowledge, on the construction costs specifically of daylight-enhancing design elements. However, previous work on the cost of green building by Chegut et al. found a marginal increase in cost to build, and more notably, a significant increase in design fees. Additionally, the work revealed that green construction projects take longer to complete [51].

awarded the same attention on a financial balance sheet. This work shows that daylight can have an appreciable impact on the operating income of a building, and thus should be considered in all stages of project financing and investment. The added value in rent prices can offset potential costs associated with designing and constructing for daylight optimization. Moreover, understanding the financial value of daylight can inform building and planning policies to equalize rent prices and ensure that daylight is available to all. The 5–6% premium identified in this work is based on the existing commercial office market in Manhattan. While the study is specific to New York City, previous literature shows that the results are likely reflected in major office markets around the world. By understanding the current value of daylight in a particular market, stakeholders in the building sector are incited to recognize the importance of designing and constructing with daylight in mind.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
Description of data sets used in the analysis: Compstak, NYC DOITT, NYC MapPluto, GBIG, and Geotel.

Data Source	Description
CompStak	CompStak is a database of crowd-sourced commercial lease contract data that is cross-checked against multiple broker submissions. It includes net effective rent (the actual amount of rent paid by tenant, i.e. the starting rent minus landlord concessions), as well as contract characteristics (space type, least transaction type, lease term duration, rent free period, sublease, transaction floors, tenant broker, landlord broker, and landlord concessions) and building characteristics (building class, building age, and renovation year) [40].
New York City Department of Information Technology and Telecommunications (NYC DOITT): 3D Building Massing Model	The NYC DOITT three-dimensional building massing model is based on a 2014 aerial survey of the city, developed to a mix of Level of Detail (LOD) 1 and 2. LOD is a standard specification used in building information modeling to indicate the resolution to which the model is developed [30].
New York City Department of City Planning: MapPLUTO	The MapPLUTO dataset from the NYC Department of City Planning provides additional building characteristics [49].
Green Building Information Gateway (GBIG)	The GBIG database, authored by the U.S. Green Building Council, lists LEED certified projects around the world [42].
Geotel	The Geotel telecommunications infrastructure database lists the buildings that are fiber lit (are connected to a high-speed fiber optic cable) [43].

Table A2
Description of variables in the hedonic model specification.

Variable	Description
Dependent Variable	
Net effective rent	We use the net effective rent in U.S. Dollars as our dependent variable. CompStak defines net effective rent as the "actual amount of rent paid (subtract[ing] lease concessions from starting rent)" [40] . In the model we use the logarithm of the net effective rent to adjust for right skewness and to be able to clearly interpret the resulting coefficients. We drop observations for which the net effective rent is not listed.
Variable of Interest	
Spatial Daylight Autonomy ($sDA_{300/50\%}$)	$sDA_{300/50\%}$ is a value between 0 and 100% indicating how much of a floor receives minimum 300 lux for 50% for all occupied hours ($sDA_{300/50\%}$). We assume the occupied hours to be standard office work hours from 8am to 6pm, Monday through Friday. We assume the occupied hours to be standard office work hours from 8am to 6pm, Monday through Friday. We separate the results into three categories: low daylight (0–55%), high daylight (55–75%), and very high daylight (75–100%). The ranges are based on the LEED recommended 55% and 75% thresholds for good daylight autonomy in commercial office spaces [15]. We adopt these thresholds because they are widely applied and understood within the building sector, and currently guide the daylighting design of contemporary buildings.
Market Conditions (Location Fixed Effects)	
Submarket	We use the real estate broker definition of neighborhoods as provided to CompStak to control for the location fixed effects. There are 24 neighborhoods specified in the data: Chelsea, City Hall Insurance, Columbus Circle, Financial District, Gramercy Park Union Square, Grand Central, Hudson Square, Hudson Yards, Madison/Fifth Avenue, Midtown Eastside, Murray Hill, NoHo Greenwich Village, North Manhattan (no observations), Park Avenue, Penn Station, Sixth Avenue, SoHo, Times Square, Times Square South, Tribeca, UN Plaza, Upper Eastside, Upper Westside, World Trade Center. During estimation, we consider the categorical location fixed effects relative to a base neighborhood, Grand Central.
Macroeconomic Conditions (Location Fixed Effects)	
Period of Transaction	We transform the lease transaction commencement date into time periods to control for macroeconomic conditions in the economy, so-called time fixed effects over the January 2010 to December 2016 lease period. To do so, we divide commencement dates into year-quarter intervals. During estimation, we consider the categorical time fixed-effects relative to a base period, year 2010, quarter 1.
Contract Term Condition Variables	
Space type	Consider only "Office" spaces; we drop other space types.
Lease transaction type	Consider only "New Lease" spaces; we drop other types.
Lease term duration	We include all leases that are less than 50 years long, divided into 5-year categories: 0–5 years, 6–10 years, 11–15 years, 16–20 years, 21–25 years, 26 and over. 72% of the leases are for 10 years or less. We drop the four outlier observations with a lease duration over 50 years. We estimate the incremental value of lease duration relative to a base lease term, 6–10 years.

(*continued on next page*)

Table A2 (*continued*)

Variable	Description
Free rent period	Duration of rent-free period in months. We divide the data into 6-month categories: no free rent, 6 months or less, 7–12 months, 13–18 months, 19–24 months, over 24 months. We estimate the incremental value of rent-free periods relative to a base rent-free period, 6 months or less.
Sublease	A binomial variable denoting contracts that allow sublease provisions or not (1 = Yes, 0 = No).
Partial floor contracts	A binomial variable denoting contract-floor that is for partial floor, and does not encompass the full floor space (1 = Yes/Partial, 0 = No/Entire).
Multiple floor contracts	A binomial variable denoting contract-floor that is part of a multiple floor contract (1 = Yes/Multiple floor contract, 0 = No/Single floor contract).
Tenant broker	A binomial variable denoting leases that have a tenant broker or tenant brokerage firm listed (1 = Yes/Tenant broker, 0 = No/No tenant broker or brokerage firm listed).
Landlord broker	A binomial variable denoting leases that have a landlord broker or landlord brokerage firm listed (1 = Yes/Landlord broker, 0 = No/No landlord broker or brokerage firm listed).
Landlord concessions/work type	All landlord concession types are included as categorical variables ("as-is", "tenant improvements", "built to suit", "new building installation", "paint and carpet", "pre-built", "turnkey", "other"). One additional category "not specified" is added for observations where the landlord concession is not listed. We estimate the incremental value of each lease concession relative to a base lease concession type, tenant improvements.
Transaction floor number	Transaction floors are divided into 15 floor intervals (0–15, 16–30, 31–45, 46 and over). We estimate the incremental value of floor height relative to a base floor height, floors 0–15.
Building Characteristic Variables	
Building class	Buildings are listed as categorical variables (Building Class A, B, or C). We drop observations for which the class is not listed. We estimate the incremental value of building class relative to a base building class, Class A.
Building age	We calculate the age of the building in the year of the lease transaction, taking the difference between the transaction year and the year the building was built. We include both the building age and the square of the building age in the model. Included as a continuous variable.
Renovated building	A binomial variable denoting buildings that are renovated (1 = Yes/Renovated, 0 = No/Not renovated).
LEED certification	A binomial variable denoting buildings that have a LEED certification (1 = Yes/LEED certified building, 0 = No/No LEED certification). If a building has multiple full-building LEED certifications, we keep only the latest certification. We consider only full-building certifications in this analysis, excluding certifications that do not apply to office buildings, such as retail or school certifications. We drop certifications that are for individual floors or spaces within a building, as they do not apply to the full building.
Fiber lit buildings	A binomial variable denoting buildings that are fiber lit (1 = Yes/Fiber lit, 0 = No/Not fiber lit). Observations that have no data are assumed to be not fiber lit.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2019.106503.

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