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The Effect of Office Design on Workstation Lighting: A Simulation Study

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ABSTRACT

It has long been recognised that the lit environment in open-plan office space is influenced by the density and properties of the installed furniture. Indeed, the Lumen Method includes a procedure involving look-up tables to account for the effects of workstation size, partition height, and partition reflectance on the mean working-plane illuminance. As part of a larger project on open-plan office environments, we used the LightscapeTM simulation tool to further explore the effect of office design on the lit environment in workstations. The office design variables of interest were workstation size, partition height, workstation reflectance, ceiling reflectance, and ceiling height. In addition to desktop illuminance, our outcome variables included illuminance distribution and partition luminance. We performed simulations for combinations of these parameters for fourteen common lighting designs for North American open-plan office space, including direct prismatic and parabolic luminaires, and indirect and direct/indirect luminaires. The results are expressed in simple linear or curvilinear relationships between office design variables and luminous variables. Results follow expected trends, and are consistent with previously published work in this area. Furthermore, in going beyond mean desktop illuminance, our results extend knowledge of the relationships between office design variables and the luminous environment.

1. Introduction

The primary design criterion for office lighting continues to be desktop illuminance. The most common method used to predict desktop illuminance at design time, the Lumen Method [IESNA, 2000], was originally developed assuming that there were no obstructions of any kind within the space. However, it has long been recognised [e.g., Spencer, 1957] that obstructions can substantially reduce the desktop illuminance in a real space, depending on the geometrical relationship between the obstruction and the working plane. Such considerations are particularly important in the open-plan office environment where the nature of systems furniture results in many obstructions between sources of light (direct and reflected) and the working plane (the desktop), and where the desktop directly abuts one or more vertical obstructions (cubicle partitions).

There have been a number of studies investigating the effect of obstructions on luminous conditions, and the IESNA Handbook [IESNA, 2000] now includes a modified version of the Lumen Method for calculating mean working plane illuminance within open-plan workstations. However, these previous studies are limited either because:

1. they did not include the full range of workspace parameters of interest; or,
 2. they did not examine the full range of dependent variables of interest,
- or because they were deficient in both. In fact, with respect to dependent variables, previous studies have focussed almost exclusively on desktop illuminance. In light of these deficiencies, we decided to pursue our own study. In the Discussion section below, we will describe the previous studies in more detail in comparing their results to the results of our study.

Due to space limitations we cannot report our study in its entirety here, for more information see Newsham & Sander [2002].

2. Methods & Procedures

2.1 Selecting a tool

Previous studies into the effect of obstructions have adopted one of two methods:

1. measurements in full-scale rooms or scale models; or
2. analytical modelling.

Given the range of independent and dependent variables in this study, it seemed impractical to employ the physical modelling approach, which left us with analytical modelling (simulation). Previous investigators have developed their own analytical models. However, there are now several publicly-available tools to choose from, capable of doing a much better job than any model we could develop ourselves given the resources available.

We considered both RadianceTM and LightscapeTM as potential tools. Radiance uses primarily a ray-tracing method, whereas Lightscape uses primarily a radiosity model. Radiance is generally considered more accurate [Houser et al., 1999; Lee & Maunder], but (at the time we began this work) was more difficult to use and required more computing power. We considered the errors due to mistakes in operation to be a serious risk, and so we opted for Lightscape version 3.2.

All lighting simulation tools are known to have limitations in the prediction of absolute luminous values, even for relatively simple spaces. However, it is important to note the difficulties in making comparisons to measured values in real spaces. First, it is known that errors in field-photometry (e.g., using a handheld luminance meter to measure the luminance at a spot on a real surface) can be of the order of 10%. Secondly, it is notoriously difficult to accurately evaluate the surface properties of a material (reflectance, specularly etc.) in order to input them into a model. Thirdly, differences can be expected between the photometrics of the luminaires in the simulations (based on manufacturers' data) and actual performance in a real space. As a result, we can have more confidence in the relative values output from a simulation tool than the absolute values. For example, we can have more confidence in a statement such as "increasing the height of partitions 12" decreased the desktop illuminance by 10%," than in the statement, "increasing the height of partitions 12" decreased the desktop illuminance from 500 to 450 lux." Nevertheless, in comparing our results to design criteria, or to luminous values demonstrated to be important to occupants in human factors studies, we need to use absolute values. Given this uncertainty, inherent at design time, we will consider the absolute predictions as appropriate for comparative evaluation of options at the early design stage, though they may not accurately predict the luminous conditions in the final space as-built.

2.1.1 Validation exercise

To gain a better understanding of the limitations of Lightscape in predicting absolute luminous values, we conducted a validation exercise. For this exercise we simulated the luminous environment in a full-scale mock-up office space under three different lighting designs. The predicted values of illuminance and luminance at certain points were compared to the values measured when those designs were physically installed in the space during an experiment on lighting quality in offices [Veitch & Newsham, 1998]. Reflectances and photometric data were taken from a similar exercise carried out by Houser et al. [1999] in the same space. Figure 1 shows a visual comparison between Lightscape simulations and photographs of the real space. Table 1 compares the predicted and measured luminous values.

Visually, the renderings from Lightscape match the photographs of the real space quite well. All of the major differences between lighting designs are reflected in the renderings. Note, for example, the luminance patterns on the distant walls, the ceiling brightness, and the shadowing on the partitions behind the computer and below the partition-mounted storage elements.

Numerically, the predicted values of luminance and illuminance differ from the measured values by up to 20%. The predicted luminance on the partitions behind the computer tends to be higher

than the measurements for the direct lighting design, and lower than the measurements for the indirect lighting design. A similar observation can be made for the desktop illuminances. Nevertheless, the trends between the lighting designs are similar for both the measurements and the simulations. Partition luminances are highest for the indirect lighting design, next highest for the lensed design, and lowest for the louvered design. Desktop illuminances are highest for the indirect design, next highest for the louvered design, and lowest for the lensed design.

The agreement between the measurements in the real space and predictions from the simulations are reasonable in the context of this work; i.e., relative comparisons between lighting systems at the design stage. The agreement is also in line with IESNA [2000, p. 9-52], which states that differences of up to 20% can be expected between the predictions of detailed analytical methods and field measurements.

2.2 Space design variables

Table 2 shows the independent variables related to the space design for this study. These are all variables where effects on luminous conditions have been demonstrated by other studies, or for which we would expect effects.

There are too many variables and too many values of each variable to study all combinations in a reasonable time with our resources. Our approach is to consider Workstation Size, Partition Height, Ceiling Height and Reflectances as independent variables – each will be looked at separately as variations on a base case (Workstation Size= 10' x 10', Partition Height= 64", Ceiling Height= 9' and Reflectances= 80/50/20).

The workstations modelled in this study did not include storage elements such as shelves, cupboards, or binder bins, which are often suspended from partitions above the desk surface. We made this choice to maintain consistency across simulations for different partition heights – the shorter partitions could not have supported storage elements, and the taller partitions would have supported them at differing heights. The effect of storage elements was addressed in Newsham & Sander [2002].

2.3 Lighting Design Variables

Table 3 shows the lighting designs simulated in this study. These designs were chosen after consultation with leading North American lighting designers. Our goal in this consultation was to identify the most commonly specified lighting designs for open-plan office space. Although common in practice, some of these designs may violate manufacturers' recommendations for spacing ratios.

The specific fixtures simulated were those that came with the Lightscape fixture library¹. While they are modelled on a particular fixture from a particular manufacturer, we expect the results that emerge from the study will allow us to draw conclusions about generic fixture types. In all cases the output of the fixture was multiplied by a factor of 0.8 to account for total lumen depreciation (lamp ageing, dirt accumulating on fixture etc.), to more accurately reflect the maintained luminous conditions to be expected.

Note, this study addresses only electric lighting, there was no daylight simulated in these studies. This is reasonable because it is the common design assumption, so that adequate lighting is also provided at night. In addition, in many deep-plan office buildings, interior workstations receive no appreciable daylighting even during the day. In fact, it is commonly assumed that there is no appreciable daylight contribution at points further than 15' from a window. Effects on daylighting are reported in Reinhart [2002].

¹ 1x4, 1-lamp fixtures (P11, L21) were simulated by halving the output from a 1x4 2-lamp fixture, since no 1-lamp fixture was available in the Lightscape fixture library.

2.4 Specification of outputs

Values for all the points shown in Figure 2 were predicted using Lightscape simulations. We summarised the very large number of results from individual data points into a small set of performance parameters. Table 4 summarises these parameters. These particular points and parameters were chosen to be compatible with the common performance parameters in various standards, the data points chosen in Veitch & Newsham [1998], and to be representative of certain design criteria or measures shown to correlate with subjective responses.

2.4.1 Multi-workstation evaluations and “dithering”

Even for a regular array of light fixtures and workstations, no one workstation will necessarily have the same relationship to the luminaires as any other workstation, as shown in Figure 3. So taking predicted values from only one workstation might bias the results. Therefore we decided to take predictions from six workstations.

Even then, no one arrangement of workstations (WS's) to luminaires is unique or favoured – for most typical general illumination applications there is no reason why the whole array of workstations could not be shifted a little in any direction relative to the luminaires. To account for this, we adopted a process we call “dithering”, running each simulation five times for each WS/luminaire combination. Four of these moved the WS's a few feet in various directions (where appropriate), and the fifth rotates the luminaires by 90° (where appropriate), as shown Figure 3. By simulating six workstations in five different relationships to the luminaire grid (or five “dither” states), we obtained a representative data set, without it becoming unmanageable.

2.5 Other simulation information

A 100' x 100' floor space was used with 12 identical workstations located near the centre of the space, so as to minimise the effects of the boundary walls. This arrangement of the workstations is typical of practice. Data were taken from six of the 12 workstations, as shown in Figure 3. These six were chosen to include workstations with differing numbers of neighbouring workstations, to include the effect of neighbouring workstations on the lighting distribution. Light fixtures were located according to the designs specified in Table 3. Generally this involved regular arrays of luminaires over the whole floor, so that distant surfaces were appropriately lit. In this way we achieved realistic lighting conditions on the workstations being studied, without including a whole floor of workstations, which would have made calculation time prohibitive.

2.5.1 Simulation time vs. accuracy

The radiosity simulation process involves iterative redistribution of light energy between the tens of thousands of surfaces in the model. Complete distribution of the energy, so that all surfaces are in equilibrium with each other, signifies the final completion of the simulation. Unfortunately, for relatively complex simulations like ours, 100% distribution of energy can take a long time to achieve. Using a number less than 100% represents a trade-off between potential accuracy and simulation time. Desktop illuminance does increase by around 5% by running the simulation beyond 99% energy distribution to 99.99%, however, this quadruples simulation time. In absolute terms, the increase in simulation time is manageable for a simple simulation, but is unacceptable for a complex simulation. Running the simulations longer for the simple cases only would introduce inconsistencies between lighting designs. Given this information, we decided to stop the simulations at 99% energy distribution, which strikes a reasonable compromise between practicality and potential accuracy. Note, any underestimates introduced will be similar for all lighting designs and should not compromise relative comparisons.

3. Results

The purpose of this paper is not to present results for individual lighting designs, but to present general trends in how office design affects the luminous environment. In the following sections we illustrate these relationships for each of the luminous outcome variables.

3.1 Desktop Illuminance (E_{desk})

3.1.1 Effect of partition height

Figure 4 shows the effect of partition height on the predicted desktop illuminance from the simulations; other design parameters are as for the base case defined in Table 2. Each point on the Figure is the median of 240 data points (8 points per desktop x 6 WS x 5 "dithers"). Lighting design I36 was excluded from this analysis because it uses partition-mounted fixtures, so partition heights differing from the base case were not relevant. In this plot we are looking for general relationships, so the desktop illuminance is expressed as a fraction of the desktop illuminance for the same lighting design but with no partitions above desktop height², best expressed in this case as a partition height equal to desktop height (30"). In this case, the 'no-partitions' case (30") is the obvious normalisation point, rather than the base case partition height (64"). Normalising to the no-partitions case will allow for a better comparison with work by other researchers, who have generally examined the effect of obstructions with reference to an empty room.

There is a clear and expected trend for E_{desk} to decrease with increasing partition height. This main effect appears to interact with luminaire type, and again, this is as expected. Parabolic louvered fixtures, which generally have a greater fraction of their light output directed straight down, are least affected in a relative sense by an increase in partition height. Fixtures with a prismatic lens, with more light directed off the vertical axis, tend to be more affected by partition height, because a greater proportion of the light reaching the desktop would arrive from angles that are blocked by vertical obstructions. Fixtures with an indirect component, and which rely most on inter-reflection of light to reach the desktop, are most affected.

One anomaly is the fixture type I43, shown in Figure 5. This fixture aims to provide some of the characteristics of an indirect fixture in a ceiling-recessed mounting. Nevertheless, in appearance it more closely resembles a recessed prismatic-lensed fixture, and its curve in Figure 4 concurs with this observation. Therefore, in future categorising of fixtures by predicted performance, I43 will be included with the prismatic fixtures.

Given the grouping by fixture type displayed in Figure 4, it seems reasonable to derive general relationships by fixture type, these are shown in Figure 6.

3.1.2 Effect of workstation size

Figure 7 shows the effect of workstation size on the predicted desktop illuminance from the simulations. In this case the data are normalised to the value for a square cubicle workstation of size 10', the base case size, because there is no obvious reason (as there was for partition height, for example) to normalise to something other than the base case. Lighting designs I15 and I36 are not included because they employ fixtures at the centre of workstations and on partitions respectively, thus the number of fixtures increases as the workstation size decreases.

² This was actually modelled by removing all partitions, but the difference between having no partitions and having partitions up to desktop level is insubstantial. Other workstation furniture was included in the 'no partitions' simulation.

In Figure 7 there is a clear trend in the expected direction. As workstation size decreases and the density of obstructions in the space increases, E_{desk} decreases. In this case there is no obvious grouping by fixture type, so the results from all fixture types are used together to derive a general relationship, as shown in Figure 8. For this relationship we can hypothesise a non-linear trend, because the number of obstructions would be related to the area of the workstation, not the linear size.

3.1.3 Effect of workstation reflectance

Figure 9 shows the effect of workstation reflectance on the predicted desktop illuminance from the simulations. In this case the data are normalised to the value for reflectances of 80/50/20, the base case values. The results show the expected trend: as the workstation (partitions and desktop) reflectance decreases, so does E_{desk} . The principal mechanism to explain this effect is the reduced reflection of light from the partition closest to the data point. Therefore, it is no surprise that there is an interaction with fixture type – those fixture types that are most reliant on reflection of light from surfaces to reach the working plane have the largest dependency on the reflectance of workstation surfaces. General relationships by fixture type are shown in Figure 10.

3.1.4 Effect of ceiling reflectance

Figure 11 shows the effect of ceiling reflectance on the predicted desktop illuminance from the simulations. In this case the data are normalised to the value for reflectances of 80/50/20, the base case values. The results show the expected trend, as the ceiling reflectance increases, so does E_{desk} . However, as expected, there is a strong effect of luminaire type. Fixtures recessed in the ceiling with primarily direct delivery of light to the desktop exhibit only a small effect of ceiling reflectance. Fixtures with a substantial indirect component, for which the ceiling is the target surface and principal light distribution medium, exhibit a strong effect.

Generic relationships, presented separately for direct fixtures and fixtures with an indirect component, are shown in Figure 12. Note that the extension of the curves below 80% reflectance is an extrapolation of available data, and should be treated with some caution.

While increasing ceiling reflectance might be an effective way of boosting desktop illuminance, if the reflectance is too high there is the risk that the ceiling itself can become a source of glare.

3.2 Illuminance Uniformity (U_{Edesk})

In general, any change in E_{desk} due to a change in office design parameters changes U_{Edesk} in the same direction. The effect of workstation and ceiling reflectance are very small, but the effect of partition height and workstation size are substantial, and are shown in Figure 13 and Figure 14 respectively.

The effect of partitions is striking, with the exception of one lighting design (I14) none of the measured points on the desktop had an illuminance less than 80% of the mean illuminance in the no-partitions case. However, in most cases, the shadowing caused by even 48" partitions results in some data points falling below the 80% criterion, and, as expected, as partition height increases uniformity generally declines (U_{Edesk} increases).

Similarly, as workstation size decreases the shadowing from the increased density of obstructions in the space results in a decrease in uniformity. Interestingly, three of the lighting designs with indirect components show uniformity improving from 10' to 8' workstations, before getting decidedly worse again for 6' workstations. Our belief is that this is an anomaly of the particular relationship between luminaire and workstation layout for the 8' case, rather than a property of the luminaires involved.

Illuminance distribution and uniformity are addressed in more detail in Newsham & Sander [2002].

3.3 Partition Luminance behind Computer ($L_{pt3,4}$)

3.3.1 Effect of partition height

Figure 15 shows the effect of partition height on the predicted luminance behind the VDT. $L_{pt3,4}$ includes only those luminance points relevant for partition heights as low as 48". Lighting design I36 was excluded from this analysis because it uses partition-mounted fixtures. Because the no-partitions case is not meaningful for partition luminance, the values have been normalised to the base case partition height of 64".

There is a clear and expected trend for $L_{pt3,4}$ to decrease with increasing partition height and therefore spatial obstruction. There is no consistent effect of fixture type, and a generic relationship for all fixture types, derived from a linear fit to the points, is shown in Figure 16.

3.3.2 Effect of workstation size

Figure 17 shows the effect of workstation size on the predicted partition luminance from the simulations. In this case the data are normalised to the value for a square cubicle workstation of size 10', the base case size. Figure 17 shows results for all lighting designs except I15 and I36, where the number of fixtures increases as the workstation size decreases. There is a trend in the expected direction. As workstation size decreases and the density of obstructions in the space increases, $L_{pt3,4}$ decreases.

In this case there is no obvious grouping by fixture type, so the results from all fixture types (except I15, I36) are used together to derive a general relationship, as shown in Figure 18.

3.3.3 Effect of workstation reflectance

Figure 19 shows the predicted effect of workstation reflectance on partition luminance. In this case the data are normalised to the value for reflectances of 80/50/20, the base case values. The results show a strong trend, as the workstation (partitions and desktop) reflectance decreases, so does $L_{pt3,4}$. Since luminance for diffuse surfaces is simply a function of the light incident on a surface and that surface's reflectance, this strong relationship is entirely expected.

There is no substantial effect of luminaire type, and a general relationship applicable to all fixture types is shown in Figure 20. The best-fit curve has a slight non-linear component, and is forced through the point (0,0); i.e., $L_{pt3,4}$ must be zero when reflectance is zero. The slight non-linearity is explained by consideration of inter-reflection effects. As reflectance increases more light leaves the target surface that could be reflected back to the target surface from other surfaces.

3.3.4 Effect of ceiling reflectance

Figure 21 shows the effect of ceiling reflectance on the predicted partition luminance from the simulations; other design parameters are as for the base case defined in Table 2. In this case the data are normalised to the value for reflectances of 80/50/20, the base case values.

The results show the expected trend, as the ceiling reflectance increases, so does $L_{pt3,4}$. However, as expected, there is a strong effect of luminaire type. Fixtures recessed in the ceiling with primarily direct delivery of light to the desktop exhibit only a small effect of ceiling reflectance. Fixtures with a substantial indirect component exhibit a strong effect. General relationships, presented separately for direct fixtures and fixtures with an indirect component, are shown in Figure 22.

3.4 Effect of Ceiling Height

We ran simulations for two ceiling heights, 9' and 8', for each lighting design, where appropriate. Lighting designs using suspended luminaires were excluded from the simulations with 8' ceilings because this would require unrealistically short suspension lengths or fixtures hanging unacceptably low.

When the ceiling is lowered there are mechanisms acting to both increase and decrease illumination. For data points directly below a fixture (or close to directly below) the reduction in distance to the principal illumination source will increase illumination. For data points between luminaires, the shorter distances to luminaires is counteracted by the larger angle between the line joining the illumination source and the data point and the normal to the illumination source. In addition, when the ceiling is lowered partitions will cause shadowing from a greater number of distant luminaires.

The net result is that when the ceiling is lowered from 9' to 8' (with other base case workstation parameters held constant) maximum E_{desk} increases and minimum E_{desk} decreases, in most cases. Therefore, uniformity is also decreased. Median E_{desk} changes by +3 to -18%, an increase occurring for the partition-mounted indirect fixtures (I36), and the biggest decreases generally occurring for the designs with widely dispersed luminaires.

4. Discussion

4.1 Comparison to other work

4.1.1 Comparison to other research studies

The literature contains several previous studies that have addressed the effect of obstructions in spaces on the luminous environment. Egger [1984] used a custom computer program to examine the effect of a single partition in front of the desk on illuminance in the working zone. The partition was 2.4 m (7' 10") wide and 1.7 m (67") high, and the base lighting system was 1-lamp louvered fixtures. For a 50% partition reflectance, the reduction in illuminance compared to the no-partitions case was 22%. This compares with 20% in our study for lighting design L21 with 64" partitions. Changing the reflectance of the partition had only a minimal effect on the outcome. Increasing partition reflectance from 50 % to 90% increased desktop illuminance by only 3%, similarly, decreasing reflectance to 10% reduced desktop illuminance by 3%. In our study, with a larger area of partition enclosing the desk, decreasing reflectance to 20% reduced illuminance by about 9%.

Briggs [1984] constructed a full-scale model of an open-plan office space within a small room (20' x 20'). He varied workstation size (6' x 8' and 9' x 12'), partition height (65" and 75"), partition reflectance (79% and 15%), and 2' x 4' luminaire type (lens and louver). He also examined the effect of luminaire location relative to the workstation by conducting measurements for luminaires in the centre of each cubicle, or at the corners of the cubicle ('straddling'). Going from the high reflectance case to the low reflectance case reduced illuminance at working plane height within the cubicle by 40% for the lensed fixtures in the smaller workstation with the higher partitions, and by 33% for the louvered fixtures in the same workstation. For the louvered fixtures in a larger cubicle, the reduction was 31%. For the lensed fixtures, going from the larger to the smaller cubicle decreased illuminance by 62%. A change from lensed to louvered fixtures did not change working plane illuminance. Changing the luminaire location from the corners of the workstation to the centre tripled the illuminance. Rotating the louvered fixtures 90° had a 15% effect. In general, these effects are much bigger than those reported elsewhere and in our study. One possible explanation is that most of the measurements were conducted for the small, high workstation with the luminaires in the straddling location, with all luminaires located outside of the workstation walls.

Carter & McEwan [1986] used a custom computer program to investigate the effect of obstructions above the working plane on illuminance uniformity. They note that '... in all cases examined, obstruction causes a reduction in uniformity over the task area.' The same authors [McEwan & Carter, 1987] conducted measurements in office spaces before and after the introduction of furniture. Note that the density of furniture, including partitions, was much lower than that considered in our study. Nevertheless, they observed average reductions in illuminance of 8 – 10 %, with maximum reductions at specific points of 35 – 47%. They also found that 5 – 11% of the working plane illuminances were below 80% of the mean illuminance.

Carter & Bougdah [1992] also conducted investigations using a custom computer program. Compared to an unobstructed space, 1.25m (49") partitions reduced working plane illuminance by around 9%, 2m partitions (79") brought about a reduction of around 15%, for a prismatic lens diffuser. This compares to an 11% reduction for a 48" partitions for our P22 design, and 35% for a 72" partition. The disparity may be due to the fact that the density of furniture in their studies, even their 'heavy' case, was lower than in our study. They note that 'Variation of room and obstruction surface reflectance over a full range of values ... caused negligible effect ...', and, '... obstructions have a major effect on illuminance uniformity conditions over the task areas ...'; both statements support our own findings.

Lupton, Leung & Carter [1994] conducted photometric surveys in office buildings without furniture, with standard obstructions introduced by the investigators, and when furnished. In the cases with the highest obstruction density, providing the best comparison with our study, working plane illuminance was reduced by 10 – 30% compared to the unobstructed condition. The 30% reduction came from the highest density, real furniture case, which featured a recessed parabolic fixture and partitions of approximately 1.75m (69"). A 72" partition with our L32 lighting design produces a reduction of 34%. They also note that lensed fixtures suffer greater illuminance loss than louvered fixtures, saying, 'The reason for this is presumably that light from luminaires with direct light distributions is not intercepted to the same extent by vertical obstruction than from luminaires with pronounced sideways intensity distributions.'; this agrees with our findings.

Hadwan et al. [2000] both measured and predicted working plane illuminance reduction due to the introduction of furniture into a space. Predictions were made using their own simplified method, and by simulating the space with Lightscape. Their 'heavy' furniture case comes closest to our own work, though it only featured a single partition. The measured illuminance reduction was 10.5%, that predicted by Lightscape was 13.9%, and that predicted with their own method was 12.7%

Siminovitch, Navvab & Rubinstein [1987] measured the effects of obstructions using a scale model. The modelled lighting system was 2' x 4' lensed fixtures on 8' centres. Most measurements were conducted for a desk and single partition in front of the notional observer. They varied partition height (4', 5' and 6' equivalent), and reflectance (10% and 80%). In addition, they modelled another workstation configuration with partial side partitions. Part of their investigation involved taking measurements for different workstation orientations and workstation-to-lighting geometries, similar to our dithering process. Compared to an unobstructed space, a 4' partition reduced task plane illuminance by 18%, a 5' partition by 27%, and a 6' partition by 31%. For our P22 case, a 48" partition reduced desktop illuminance by 11%, a 64" partition by 28%, and a 72" partition by 35%. Lowering partition reflectance from 80% to 10% for a 5' partition reduced illuminance by an average of only 8%. In our case, lowering reflectance from 50% to 20% for a 64" partition reduced illuminance by 10%. They estimate that the addition of the partial sidewall partitions reduced task illuminance by a further 5 – 10%. They also note that the occupant's own shadow, not modelled in their or our study, '... can reduce task illuminance levels by as much as 25%.'

Choi & Mistrick [1995] also conducted an investigation using a custom computer model. They modelled 8.2' x 8.2' cubicles, and varied luminaire type, layout, partition height (49", 59", and 69"), partition reflectance (20% and 60%) and furniture within the cubicle. Compared to the

unobstructed case, and for direct recessed fixtures, 49" partitions reduced illuminance at task height in the centre of the cubicle by around 16%, the 59" partitions by around 23%, and the 69" partitions by around 30%. In our study, for all lighting designs, 48" partitions reduced desktop illuminance by 4 – 22%, 64" partitions by 18 – 34%, and 72" partitions by 25 – 38%. Compared to partitions with 60% reflectance, changing partitions to 20% reflectance reduced illuminance by around 18%. In our study, for all lighting designs, a 20% workstation reflectance reduced desktop illuminance by 8 – 14% compared to 50% reflectance. They also note that '... an overhead cabinet causes significant light loss on the desk.' They also examined illuminance uniformity, and found that it decreased with decreasing partition reflectance and increasing partition height, again, in agreement with our findings.

Misir, Onaygil & Enarun [1999] took measurements in a small, full-scale laboratory while varying the number of partitions, their height (0.8 m (31"), 1 m (39"), 1.3 m (51"), and 1.6 m (63")), and their reflectance (80%, 52%, and 7%). The light fixtures were not typical of North American luminaires, being narrow, louvered fixtures with a single 16 W lamp. For the 63" partition and a single partition, lowering partition reflectance from 80% to 7% lowered working plane illuminance by 7%. In our study, for the L21 lighting design, lowering workstation reflectance from 50% to 20% reduced desktop illuminance by 9%. With four 52% reflectance partitions forming a cubicle, 63" partitions lowered illuminance by 17% compared to a space with no-partitions. In our study, with 50% reflectance and 64% high partitions, the reduction was 20%.

4.1.2 Comparison to the Lumen Method

The Lumen Method [IESNA, 2000] does contain additional procedures that allow for the prediction of mean working plane illuminance in partitioned spaces. Workstation size, partition height and partition reflectance are all potential variables. As published, the method does require the use of several look-up tables, and interpolating or extrapolating values from these tables. Note that the accuracy of the Lumen Method is estimated at $\pm 10\%$ [IESNA, 2000, p. 9-55]. We performed a limited comparison between a Lumen Method calculation to our results.

We performed a comparison for the base case workstation under the P11 lighting design. For a 100' x 100' office space, a 9' ceiling, and a 2.5' working plane:

$$\text{Room Cavity Ratio (RCR)} = 5 \times (9 - 2.5) \times (100 + 100) / (100 \times 100) = 0.65$$

From the photometric data available for the luminaire, the coefficient of utilization (CU) for this RCR is approximately 0.74. For this space, there will be 380 fixtures, each with a single lamp rated at 2900 lumens. Assuming an overall Lumen Depreciation of 0.8 (as assumed in the Lightscape simulations):

$$\text{Mean } E_{\text{desk}} = 380 \times 1 \times 2900 \times 0.74 \times 0.8 / (100 \times 100) = 65.2 \text{ fc or } 702 \text{ lx}$$

This compares well with the 729 lx predicted by our Lightscape simulations for a similar case.

We then used the Lumen Method to predict mean illuminance for various partition heights, workstation sizes, and workstation reflectances. Without detailing every step in the procedure, Figure 23 compares these calculations with the predictions from Lightscape. The comparison for the effect of partition height is particularly good, the gradient of the curves being very similar. The trends for the effect of workstation size and reflectance are also similar, though the Lightscape results show a greater effect for workstation size and a lesser effect for workstation reflectance.

In general, the comparison of our results to past studies and to the Lumen Method are favourable. The direction of the effects of the various office design variables are consistent and in the expected direction, and the magnitude of the effects are in broad agreement. Previous studies have looked primarily at working plane illuminance, and, in a limited way, at illuminance distribution. Our study takes the investigation of office design effects further by looking also at

partition luminance and illuminance around the computer, and their distributions. In addition, we have added ceiling reflectance as another design variable. The agreement between our results and the results of other studies on desktop illuminance can give us some confidence in our other results too.

4.2 Generalising results for arbitrary lighting designs

Figure 6 shows the general relationship between desktop illuminance and partition height, for a given luminaire type, relative to the no-partitions (above desktop) case. So, provided the user has an estimate for the average³ desktop illuminance with no partitions for the lighting design of their choice, they can use the relationships we have derived to arrive at a desktop illuminance for a given open-plan workstation design. For any regular array of luminaires, the Lumen Method, which is in wide use, can be used to easily derive the initial, no-partitions, value.

The Lumen Method will not provide a similar starting value for partition luminance. Other methods are available to calculate luminances on vertical surfaces [IESNA, 2000, Chapter 9], but even for diffuse surfaces, these calculations are complex. However, experience making measurements in real and mock-up offices indicates that $L_{pt3,4}$ is highly correlated with E_{desk} . We investigated this for the base case workstation design. Figure 24 shows the relationship between $L_{pt3,4}$ and E_{desk} for the base case workstation for each lighting design. The two quantities are strongly correlated, and there is a dependence on luminaire type. Therefore, we pursued separate regression equations for each type, which are shown in Figure 25; the regression lines were forced through (0,0), with the assumption that when $E_{desk}=0$, $E_{pt3,4}=0$. The dependence on luminaire type is as would be expected. The more direct the light distribution, the lower the partition luminance per unit of desktop illuminance.

So the user, starting with an average desktop illuminance for the no-partitions case from the Lumen Method (or other calculation method), can calculate E_{desk} for the base case partitions (64"), and then use Figure 25 to derive $L_{pt3,4}$ for the base case. Finally, the user can use the relationships defined earlier (Figures 16, 18, 20, 22) to calculate $L_{pt3,4}$ for any given workstation design.

4.3 Accounting for the non-independence of effects on E_{desk}

We noted above that there were too many parametric combinations to perform simulations for all interactions, and that we chose to treat the main effects of office design parameters as independent for simplicity. We noted that this approach can lead to errors if the effects are not independent. Fortunately, we can make a relatively easy correction for this non-independence for E_{desk} , the most widely used measure of lighting system performance, if we assume, as suggested by Figure 6, that the relationship between E_{desk} and partition height is linear.

To appreciate the potential errors involved, see Figure 26. The line labelled (1) shows the effect of partition height on E_{desk} for the base case workstation (workstation size=10', workstation reflectance=50%), for parabolic luminaires, copied from Figure 6. The line labelled (2) shows the effect of partition height on E_{desk} for a workstation size of 8' (workstation reflectance=50%), by applying the simple multiplication factor for workstation size (0.9246 for an 8' workstation) shown in Figure 8. The line labelled (3) shows the effect of partition height on E_{desk} for a workstation size of 8' and workstation reflectance of 35%, by applying a further simple multiplication factor for workstation reflectance (0.9520 for 35% reflectance with parabolic fixtures) shown in Figure 10. These lines are the result of applying the effects independently, and they diverge slightly as partition height decreases. However, when there are no partitions above the desktop (partition height=30") all three situations should yield (virtually) the same E_{desk} ; i.e., the lines should

³ Our relationships are based on median values, whereas the Lumen Method, for example, will yield a mean value. In most cases these two types of average will be close enough to be used interchangeably. In fact, for a perfectly normal distribution, mean and median are identical.

converge on point A. This lack of convergence yields errors of around 10% for low partition heights.

Figure 26 illustrates graphically how to correct for this, for any combination of workstation parameters. First, find point B, the multiplication factor for the base case (partition height=64", workstation size=10', workstation reflectance=50%) relative to the no-partitions case. Then apply independent correction factors for the desired workstation size and reflectance (in this example, 8' and 35%), to find point R. Then draw the straight line AA' through point R. The corrected multiplication factors can then be read off line AA' for any desired partition heights.

Unfortunately, it is not possible to conduct a similar process for partition luminance ($L_{pt3,4}$) because there is no equivalent theoretical point where all lines should converge; the no partitions case is meaningless for $L_{pt3,4}$.

4.4 Example calculation for an arbitrary lighting system

Consider a large open-plan office space 120' x 120' with a ceiling height of 9' and a working plane height of 2.5'. The ambient lighting system is a 2'x4' 18-cell parabolic fixture with two 2900 lumen lamps, on 8' centres. Ceiling reflectance is 80%, perimeter wall reflectance is 50% and floor reflectance is 20%. The workstations planned for the space are 8' x 8' with an average surface reflectance of 35%, and the designer wishes to compare luminous conditions for 68" vs. 54" partitions.

We can begin by using the Lumen Method to calculate the mean desktop illuminance for an empty room:

$$RCR = 5 \times (9 - 2.5) \times (120 + 120) / (120 \times 120) = 0.54$$

From the photometric data available for the luminaire, the CU for this RCR is approximately 0.77. For this space, there will be 225 fixtures, assuming an overall Lumen Depreciation of 0.8:

$$\text{Mean } E_{\text{desk}} = 225 \times 2 \times 2900 \times 0.77 \times 0.8 / (120 \times 120) = 55.8 \text{ fc or } 601 \text{ lx}$$

We can then use Figure 26 to predict E_{desk} for 68" partitions. First, find point B, for which the predicted multiplication factor is 0.77 (Figure 6). This means that E_{desk} for the base case (64" partitions) is $601 \times 0.77 = 463 \text{ lx}$. Then find point R by applying multiplication factors for a workstation size of 8' (0.93 from Figure 8), and a workstation reflectance of 35% (0.95 from Figure 10). Therefore point R is at $0.77 \times 0.93 \times 0.95 = 0.68$. Then derive line AA'; from line AA' one can read off the appropriate multiplication factor for any partition height. For 68" partitions the multiplication factor is 0.64, and E_{desk} is: $601 \times 0.64 = 385 \text{ lx}$.

We can then use Figure 25 to derive $L_{pt3,4}$ for the 64" partition case, for $E_{\text{desk}} = 463 \text{ lx}$, $L_{pt3,4} = 27 \text{ cd/m}^2$, for parabolic fixtures. Figure 16 indicates a multiplication factor for 68" partitions of 0.95, relative to 1.00 for the 64" partition case. Figures 18 and 20 then suggest multiplication factors of 0.93 and 0.59 to modify $L_{pt3,4}$ for workstation size and reflectance respectively. Therefore, assuming independence of effects, $L_{pt3,4}$ for the workstation with 68" partitions is: $27 \times 0.95 \times 0.93 \times 0.59 = 14 \text{ cd/m}^2$.

We now wish to compare predictions for 54" partitions, so we will repeat the above process with appropriate modifications. We can predict E_{desk} for 54" partitions using the same line AA' developed above for 68" partitions. For 54" partitions the multiplication factor is 0.77, and E_{desk} is: $601 \times 0.77 = 463 \text{ lx}$.

For the 64" partition case, for $E_{\text{desk}} = 463 \text{ lx}$, $L_{pt3,4} = 27 \text{ cd/m}^2$. Figure 16 indicates a multiplication factor for 54" partitions of 1.13, relative to 1.00 for the 64" partition case. Figures 18 and 20 then suggest multiplication factors of 0.93 and 0.59 to modify $L_{pt3,4}$ for workstation size and reflectance

respectively. Therefore, $L_{pt3,4}$ for the workstation with 54" partitions is: $27 \times 1.13 \times 0.93 \times 0.59 = 17 \text{ cd/m}^2$.

Although going through this process manually is somewhat tedious, it is relatively straightforward to incorporate it into a simple spreadsheet, or other computer program.

5. Conclusions

This work extends our knowledge of the effect of open-plan office obstructions on the luminous conditions in a large office space. While being consistent with previous work reported in the literature, this work goes further in three ways:

1. By considering several luminaire types and layouts.
2. By considering outcomes other than desktop or working plane illuminance.
3. By considering how the distribution of luminous parameters is affected by obstructions.

In common with previous studies, this study found that obstructions such as office furniture can profoundly affect the luminous conditions of an open-plan space. Similarly, the properties of the furniture (partition height, workstation size, surface reflectances) can also have a substantial effect on luminous conditions.

This study reinforces the message that lighting design criteria for open-plan office spaces which do not take into account the effect of the furniture, which is common practice, are likely to be flawed. Secondly, this study highlights the importance of considering luminous parameters in addition to working plane illuminance. For example, though partition reflectance has only a small effect on desktop illuminance, it has a large effect on partition luminance. The study also shows the importance of considering light distribution. For example, Figure 13 shows that half of the popular lighting designs we considered have over 10% of desktop illuminance data points below 80% of the mean illuminance. Anecdotal evidence suggests that in real spaces (rather than our simulated ones), where there is a wider variety of furnishings within workstations and a reduced lighting design uniformity, inequities of luminous conditions between workstations can be even higher.

This study suggests the following general rules-of-thumb:

- For desktop illuminance, a reduction of 10% will occur if:
 - partition height is increased by 12" for prismatic fixtures (reduction is more like 12% for fixtures with a substantial indirect component, and 8% for parabolic fixtures).
 - workstation size is decreased from 10'x10' to 7'x7'.
 - workstation reflectance is decreased from 50% to 20% for prismatic fixtures (reduction is more like 12% for fixtures with a substantial indirect component, and 8% for parabolic fixtures).
 - ceiling reflectance is decreased by around 10% for fixtures with a substantial indirect component (reduction is negligible for direct fixtures).
- For partition luminance, a reduction of 10% will occur if:
 - partition height is increased by 8".
 - workstation size is decreased by 3' on each side.
 - workstation reflectance is decreased from 40% to 36%.
 - ceiling reflectance is decreased by around 7% for fixtures with a substantial indirect component (reduction is negligible for direct fixtures).
- Illuminance uniformity will be decreased by any change in office space design that decreases mean illuminance.

It is always important to recognise the limitations of any study of this type. The study was performed using the Lightscape simulation tool, and the results are only as accurate as the tool used to derive them. Lightscape simulations did compare reasonably well to measurements made in a mock-up office space, and our results are consistent with those from other studies and with the Lumen Method. Nevertheless, other studies comparing Lightscape simulations to measurements in real spaces have reported inaccuracies. For this reason, we advise caution when considering the absolute values luminous parameters arising from this study. We suggest that they only be considered relative to the values from another lighting/office design rather than an accurate prediction of the luminous conditions in the space as-built.

Another limitation of this study is the assumption, driven by practical considerations of simulation time, that the effects of office design parameters are independent. That is, the relative effect of partition height is the same for a 10' workstation as for a 6' workstation, and the effect of reflectance is the same for a 64" partition as for a 48" partition, for example. This assumption of independence may not be valid. To partially address this, we have developed a method for accounting for non-independence for calculations of desktop illuminance.

Also consider that although we sought to simulate the majority of popular lighting designs for open-plan spaces and to base general design guidelines on these findings, there may be other designs that do not conform with these general trends. And remember that this study sought only to address regular arrays of luminaires in spaces with regular layouts of rectilinear workstations. Finally, caution should be taken in extrapolating the results beyond the range of variables studied.

Despite these limitations, however, we think this study does provide the designer with useful guidelines for considering how office design options will affect the luminous environment experienced by the occupant. Simple graphs illustrating these effects are provided. Compared to the prevailing situation, where such effects are commonly overlooked, this is a step forward.

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Table 1. Comparison of measured luminous values and those predicted by Lightscape for an open-plan office lit by three different lighting systems. Ranges in measured values reflect measurements made in several workstations. Ranges in simulated values reflect uncertainty in the location of measurement for comparison.

	Desktop, close to computer lx		Desktop, under storage lx		Partition behind computer, upper cd/m ²		Partition behind computer, lower cd/m ²		Partition under storage cd/m ²	
	meas	sim	meas	sim	meas	sim	meas	sim	meas	sim
Lens	360-450	410-480	360-430	430	44-49	49-51	30-38	41-44	21-23	15
Louver	460-540	490-530	410-440	420	23-35	31-36	21-30	33-35	7-8	8
Indirect	610-710	480-570	430-470	410	65-80	61-63	50-60	48-50	20-27	20

Table 2. Open-plan office design variables addressed in Lightscape simulations. Base case is shown in shaded.

Variable	Range				Unit
Workstation Size		10 x 10	8 x 8	6 x 6	ft
Partition Height	72	64	48		in
Ceiling Height		9	8		ft
Reflectances*	90/50/20	80/50/20	80/35/20	80/20/20	%

* these are ceiling/workstation surfaces/floor respectively – workstation surface value applies to partition walls and desktop. Reflectance of boundary walls was fixed at 50%.

Table 3. Basic description of lighting designs used in the simulations.

Description	Size (ft)	Lamps	Layout Grid (ft)	Code
Prismatic	1 x 4	1	5 x 5	P11
Prismatic	2 x 4	3	8 x 8	P22
Prismatic	2 x 2	2	8 x 8	P32
Louver	1 x 4	1	5 x 5	L21
Louver	2 x 4	2	8 x 10	L32
Louver	2 x 4	3	8 x 10	L42
Louver	2 x 2	2	8 x 8	L53
Dir/Indirect	1 x 4	2	5 x 10	I11
Dir/Indirect	1 x 4	2	Rows @ 10'	I14
Dir/Indirect	1 x 4	2	Centred on WS	I15
Dir/Indirect	1 x 4	3	Rows @ 12'	I22
Indirect	1 x 4	2	8 x 8	I33
Indirect	1 x 4	2	1 fixture/partition	I36
Dir/Indirect	2 x 4	2	8 x 8	I43

Table 4. Performance criteria for simulations

Luminous variable	Criterion	Notes
Desktop Illuminance (E_{desk})	Median of all data points points OLU, OLL, ILU, ILL, IRL, IRU, ORL and ORU	
Desktop Illuminance uniformity (U_{Edesk})	% all data points OLU, OLL, ILU, ILL, IRL, IRU, ORL and ORU <80% of mean E_{desk}	CIBSE LG7 [1993] states "The ratio of minimum illuminance to average illuminance should not be less than 0.8 over the relevant area.
Luminance on partition behind computer ($L_{\text{pt3,4}}$)	Median of all data points points IR3, IR4, IL3 and IL4	These are the only points that are meaningful for partition heights as low as 48"

Figure 1. An open-plan office space lit with three different lighting systems. Photographs of the real space (left) are compared with Lightscape renderings (right).

Figure 2. Individual data points for a single base case workstation. Illuminances are underlined, luminances are not.

Figure 3. Relationship between lighting and workstation layouts, and shifts during "dithering".

Figure 4. Median desktop illuminance vs. partition height, normalised to the desktop illuminance with no partitions above the desktop. Prismatic fixtures are shown in yellow hues, parabolics in greens, and fixtures with an indirect component in reds. Workstation size = 10' x 10', workstation reflectance = 50%, ceiling reflectance = 80%.

Figure 6. General relationship between normalised desktop illuminance and partition height, by fixture type. Workstation size = 10' x 10', workstation reflectance = 50%, ceiling reflectance = 80%.

Figure 5. The fixture type I43, shown left in manufacturer's literature and right, in a similar design, as simulated.

Figure 7. The effect of workstation size on median desktop illuminance, normalised to the basecase workstation size (10'). In (a) results for all lighting designs are shown. In (b) the two designs which increase the number of fixtures with decreasing workstation size are excluded. Partition height = 64", workstation reflectance = 50%, ceiling reflectance = 80%.

Figure 8. General relationship between normalised desktop illuminance and workstation size. Partition height = 64", workstation reflectance = 50%, ceiling reflectance = 80%.

Figure 9. The effect of workstation reflectance on normalised desktop illuminance for all lighting designs. Partition height = 64", workstation size = 10' x 10', ceiling reflectance = 80%.

Figure 10. General relationship between normalised desktop illuminance and workstation reflectance, by fixture type. Partition ht. = 64", workstation size = 10' x 10', ceiling reflectance = 80%.

Figure 11. Effect of ceiling reflectance on normalised desktop illuminance for all lighting designs. Partition height = 64", workstation reflectance = 50%, workstation size = 10' x 10'.

Figure 12. General relationship between normalised desktop illuminance and ceiling reflectance, by fixture type. Partition ht. = 64", workstation reflectance = 50%, workstation size = 10' x 10'.

Figure 13. The effect of partition height on desktop illuminance uniformity for all lighting designs studied (I36 excluded). Workstation size = 10' x 10, workstation reflectance = 50%, ceiling reflectance = 80%.

Figure 14. The effect of workstation size on desktop illuminance uniformity for all lighting designs studied (I15 and I36 excluded). Partition height = 64", workstation reflectance = 50%, ceiling reflectance = 80%.

Figure 15. Median partition luminance vs. partition ht., normalised to luminance for base case WS. Workstation size= 10' x 10', workstation reflectance= 50%, ceiling reflectance= 80%.

Figure 16. General relationship between normalised partition luminance and partition ht., for all fixture types. Workstation size= 10' x 10', workstation reflectance= 50%, ceiling reflectance= 80%.

Figure 17. Median partition luminance vs. workstation size, normalised to the luminance for the base case workstation; results for all lighting designs except I15 and I36 are shown. Partition height = 64", workstation reflectance = 50%, ceiling reflectance = 80%.

Figure 18. General relationship between normalised partition luminance and workstation size. Partition height = 64", workstation reflectance = 50%, ceiling reflectance = 80%.

Figure 19. The effect of workstation reflectance on normalised partition luminance for all lighting designs studied. Partition height = 64", workstation size = 10' x 10', ceiling reflectance = 80%.

Figure 20. General relationship between normalised partition luminance and workstation reflectance. Partition height = 64", workstation size = 10' x 10', ceiling reflectance = 80%

Figure 21. General relationship between normalised partition luminance and ceiling reflectance, by fixture type. Partition ht = 64", workstation size = 10' x 10', workstation reflectance = 50%.

Figure 22. The effect of ceiling reflectance on normalised partition luminance for all lighting designs studied. Partition height = 64", workstation size = 10' x 10', workstation reflectance = 50%.

Figure 23. Comparing the Lumen Method and Lightscape. Predictions for the effect of office design parameters on desktop illuminance in the case of the P11 lighting design are shown.

Figure 24. Partition luminance vs. desktop illuminance for the base case workstation for all lighting designs. Partition height = 64", workstation size = 10' x 10', workstation reflectance = 50%, ceiling reflectance = 80%.

Figure 25. Partition luminance vs. desktop illuminance, general relationships by fixture type. Partition height = 64", workstation size = 10' x 10', workstation reflectance = 50%, ceiling reflectance = 80%.

Figure 26. Accounting for the non-independence of partition height, workstation size and workstation reflectance on E_{desk} , for parabolic luminaires.