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Light-Syntax Zones in Daylit Café Spaces: A Novel Method for Understanding Occupancy

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Abstract

This thesis proposes a novel method for understanding occupancy in public indoor spaces by creating hybrid light-syntax zones, based on both simulated illuminance data and simulated configuration data. Yearly illuminance profiles and spatial syntax characteristics such as physical connectivity and visual integration were examined to develop zones which theoretically have similar occupancy rates to one another. To support the light-syntax zone concept, a case study was performed in a student cafe on a university campus. Occupancy and exterior light conditions were observed for thirteen days. Occupancy rates were mapped to each seat within the cafe and analyzed for correlations with the light-syntax zone data. A significant difference was found in the occupancy rates between different exterior light conditions (direct light present, rapidly changing/intermediate, diffuse light present) in the test cafe. A slight negative correlation was found between occupancy rates and integration and physical connectivity values, which seems to indicate that the cafe users are seeking out the most secluded spaces. However, higher illuminance values also show a correlation with higher occupancy ratios. Given the map of the space, it is possible that these two variables are confounded. Further studies are necessary to determine the validity of light-syntax zones as a tool for predicting relative occupancy within an indoor space.

Acknowledgments

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Much appreciation is due to the staff of the Giacometti cafe, who put up with my scribbling notes and taking photos for many weeks.

Without the continued and enthusiastic support of my parents I could not have possibly completed this program. It is perhaps not the easiest thing to study in a country so far, both physically and culturally speaking, from your own; and I owe a great deal to the remarkable good humor and tenacity of the fellows of my program. Finally, I appreciate deeply the long-distance support of a number of wonderful friends.

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1 Introduction

How do people use the space inside a building? What factors impact where people choose to place themselves within cafes, libraries, and atria?

The patterns of usage in many spaces are determined almost entirely by the plan and layout, an idea which has been quantified and validated by space syntax theory [1,2]. Individuals moving through a space make navigational decisions based on what they can see. For example, they are more likely to follow long lines of sight and make journeys which seem perceptually "shorter" [13]. Architects can use the principles of space syntax to make sure their buildings are better optimized for their intended users, by ensuring that their buildings are intelligible and that each space within the building has a degree of connection to other spaces which is suited to its purpose.

However, daylight poses an additional challenge for designers, as it also strongly influences the way that building occupants experience and interact with that building. Previous research suggests that in a space which is undifferentiated by configuration, the presence of daylight may be a deciding factor for individuals locating themselves within that space [8]. Light also may be important to wayfinding indoors, affecting the overall impact of space syntax [3]. Factors such as visual comfort and view interest impact how people feel toward windows and glazing, and may impact how they position themselves in a space [4,5,6,22].

Both spatial configuration and lighting characteristics are key in understanding how people use a space, but it is not clear how these two organizing principles of architecture interact with one another. Previous studies which have found high correlations between the space syntax value of integration and density of occupants within a space have not examined spaces where individuals would be expected to linger for extended periods of time [2,1,3]. By contrast, studies which have focused on the effect of light on individual positioning within a space have not taken into consideration the possible effects of configuration on those choices [8]. Is it possible to find a more precise correlation to where people are in a space, using both of these criteria? Being able to predict where people are likely to be in an architectural space has profound implications for designing sustainable, comfortable, healthy buildings, as many comfort and health metrics are location- and direction-specific [17,23].

This thesis intends to combine principles of space syntax and daylight simulation to better model how occupants interact with a public indoor space. The form of the thesis is a literature review followed by an in-depth case study of a cafe on the campus of the Ecole Polytechnique Fédérale de Lausanne, including simulations of the light and syntax qualities of that space, an observation experiment, and statistical analysis.

1.1 Problem statement

Previous studies have shown a very high correlation between the visual integration of a space and its density of occupation [1]. However, even in long-term studies there is still up to 40% of the variance of human movement in public spaces which is *not* explained by the configuration of that space.

How can we improve our understanding of where people will choose to locate themselves within an inside space by refining spatial zones using daylight characteristics?

1.2 Hypotheses

This thesis has two primary hypotheses.

It postulates that the configuration properties of a public space are the dominant feature correlated to where people will choose to seat themselves. By looking simultaneously at the natural lighting of the space, the correlation can be refined and improved within each similar spatial "zone," effectively breaking it into smaller, hybrid "light-syntax zones."

The definition of combination "light-syntax zones" – areas with similar configuration and daylight characteristics – in a public indoor space should allow for a better prediction of the occupancy of each of these zones relative to each of the zones around them.

Secondary to and in support of this primary hypothesis, the research seeks to show that individual choices about location in the space vary consistently with regards to exterior light conditions.

1.3 Structure of the work

First, a conceptual method of delineating light-syntax zones was developed. Next, a case study was designed and carried out to validate the idea that a hybrid light-syntax zone can give a more accurate prediction of human movement than either the syntax or light characteristics of the space alone.

This case study was split into space selection, simulation, observation, and analysis stages. The selection of a real public space such as a cafe or library was done based on certain criteria – the usage of the space, the configuration characteristics, the daylight characteristics of the space, the overlay of these last two sets of qualities. The simulation stage took the plan and model of the test space and used them to generate a hypothetical yearly illuminance profile and various sets of spatial metrics. During the observation phase, the position of occupants and the duration of their stay throughout the day was noted over the course of thirteen observation days. Finally, in the analysis phase, the impacts of scheduling, syntax, and light condition on occupancy were examined through correlation and analysis of variance, and the statistical validity of hybrid light-syntax zones was examined.

A diagrammatic overview of the case study performed is shown in the appendix.

2 Background and literature review

The fields of space syntax, daylighting analysis and metrics, and environmental psychology all provide a wealth of suggestions about how a zoning model predicting relative occupancy might be produced.

2.1 Space syntax

Space syntax theory quantifies several intuitive concepts about how people move through space [1]. The assessment of how "integrated" a space is with its global environment, as per space syntax theory, shows strong correlation with the distribution of occupants [2]. Integration is based on two simpler concepts.

A space's "connectivity" is a measure of how many other spaces have direct routes into that space. A front room with many hallways leading away from it has a high connectivity; a broom closet at the end of a hallway has a lower connectivity. This can be analyzed based on a large grain, using a space definition such as fields of vision or "convex spaces" (the largest space which has no blocked sight lines within it), or on a small grain, using a grid laid over the space and calculating how many other grid squares each square can be directly linked to.

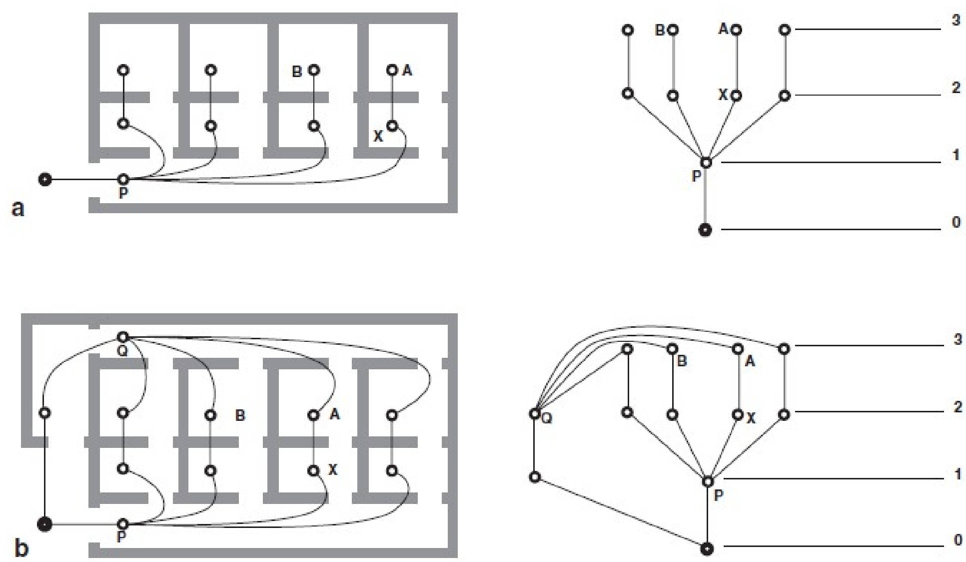


Figure 1. The process of constructing a connectivity node chart from two different sets of theoretical convex spaces [10].

A space's "mean depth" measures how many route changes it takes to access that space from any other space. For example, in a building with a very few square rooms which are all interconnected, any one space will have a low mean depth. A person moving from one space to another does not have to change their line of sight or route often, so the "perceptual depth" or distance is low. By contrast, a very complicated building with many rooms, many hallways with dead-ends and low interconnectivity will have a much higher mean depth, because a person moving from one space to any other space must change their straight-line route many more times to navigate.

The numerical integration value is calculated by finding the average mean depth of every space (or grid square) within a building. This results in the "relative asymmetry" of the space. In order to make this measure comparable to other buildings, the RA is put in a ratio with the mean depth of a “diamond graph” of appropriate size. The diamond graph has a normal distribution of nodes across all levels. The inverse of this ratio is the integration value. A higher integration value indicates a space which has a lower mean depth; a lower integration value shows a space which has a higher mean depth [10].

In an interior environment, there is likely to be a difference between physical connectivity and visual connectivity due to the placement of furniture. In this study visual connectivity and the resulting measures are treated as more significant.

2.2 Daylighting

<u>2.2.1 Impact on occupants</u>

What aspects of daylight affect a person's movement through space? Daylight serves both functional and aesthetic purposes in an architectural space, and sometimes these purposes overlap. In mostly daylit multifunctional spaces, natural light must provide enough light to work by while not causing discomfort. Levels of between 75 and 300 lux are suggested for interior spaces, depending on the nature of the activity performed there, from eating to reading [1,4]. Direct light on a horizontal work surface may be perceived as uncomfortable due to high contrast ratios. Presumably individuals who come to a cafe to work choose a space where they perceive they will have sufficient light for their task. While it seems likely that people might move to maximize their visual comfort in a space where this is possible, visual comfort is very difficult to assess in such a fluid environment. However, daylight also causes veiling glare on devices with screens, such as laptops and smartphones, which may form another basis for occupant decision-making when navigating and selecting a seat in a daylit space [24].

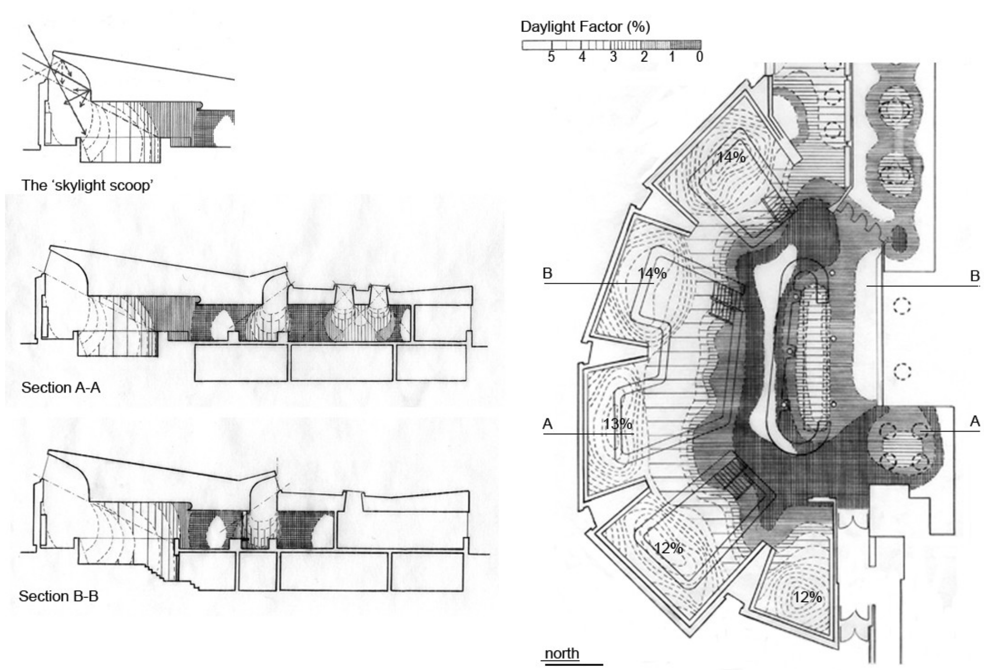


Figure 2. Light zones which create "rooms within rooms" in Alvar Aalto’s Municipal Library in Rovaniemi, Finland [15].

Beyond these more readily quantifiable measures, daylight also gives light, color, and dynamism to an architectural space [15,16]. Daylit or sunlit areas within a larger space may act as “rooms within a room,” a perceptible but intangible way of organizing space, as shown in figure 2 above [15].

It has also been suggested that a point of high light contrast may act as a directional beacon or magnet for occupants of the space, drawing their attention and possibly their movement [15]. Light, as mentioned previously, can be important in wayfinding, with areas of greater brightness within the viewfield serving to direct someone down a hallway toward an open space or down a street toward a square [3].

Daylight also provides an important connection to the outside, and individuals with freedom to choose will often fill up the seats in a cafeteria-style space next to the windows first [8]. Studies of library users have also found a preference for seats near the window, though this is likely reinforced by design choices that locate most study areas around the perimeter of the building [20]. Whether this is primarily a function of the view or of the quality of the light near the window is not clear. Studies of children in elementary school have found that given free choice, they generally prefer to sit by the window, expressing a preference both to “see what is going on” and to access maximum sunlight [21].

Clearly a building occupant integrates multiple sources of spatial information regarding view, lighting, and space configuration when making decisions about where to move and where to stay. But how much impact do each of these spatial characteristics have on the occupant's final choice?

2.1.2 Daylight metrics

The most widespread daylight metric in use in architectural is the daylight factor, defined as the ratio of illuminance at a given interior point to the horizontal exterior illuminance under an overcast sky [19]. The measure has many drawbacks, among them an insensitivity to climate, orientation, or time.

In the past ten years, several climate-based daylight metrics have become more widely accepted, most based on the horizontal illuminance. These metrics rely on a yearly illuminance profile, either from real-life measurements or simulations of the space. Daylight autonomy, proposed in 2006, is defined as the percentage of scheduled daytime hours when a certain horizontal illuminance (set by the user, at, for example, 500 lux, to meet building codes) is entirely met by daylight [17]. The Useful Daylight Index is a similar metric that calculates the percentage of scheduled hours when the horizontal illuminance falls between 100 lux and 2000 lux, focusing on light levels which are unlikely to be too dark or uncomfortably bright [18].

However, while horizontal metrics give an adequate picture of the amount of light available on the work surfaces, they do not capture the reality of light as it is perceived by an occupant of an architectural space. Measures such as vertical illuminance are correlated to how psychologically alert occupants feel [22]. Other vertical measures, such as those based on assessing the luminance within a person's field of view, are potentially a richer metric, as they provide information about brightness, available contrast, and the potential for visual discomfort [25,4].

Vertical metrics that consider the whole view field are also needed to evaluate the potential of visual discomfort and veiling glare [4,24].

2.3 Human behavior

Based on previous research, pace syntax and daylight seem to be two of the key factors that determine how individuals relate to a space, but they are certainly not the only ones. Other powerful decision-making criteria for building users as they make choices about where to stay in a space may include the interior's relationship to the exterior and the spatial relationship of one user to many users.

<u>2.3.1. Relationship to the window</u>

Windows and glazing are important to building users not just because of the amount of light they allow into the interior, but because of the view and relationship with the exterior they provide [5,26,21]. Occupants are less likely to rate a window as a source of discomfort if the view it provides is interesting, showing the high importance placed on visual stimulation [26]. The view could be a draw toward the window even if the amount of daylight provided is unimportant or uncomfortable for occupants.

<u>2.3.2. Crowding</u>

The way one person uses a space is impacted by how other people are using the same space. Many people are sensitive to feelings of crowding, and rate spaces which they perceive to be less crowded more favorably [30,31]. A loss of ability to make free behavioral choices, the need for more privacy, and a feeling of personal space being invaded can cause people to feel negatively towards crowded spaces [31]. Seat density can impact crowding, though some people are more or less sensitive to this possible stress [30].

3 Light-syntax zone conceptual framework

The basic idea of a hybrid light-syntax zone posits that different areas of an architectural space may be grouped according to similar light characteristics and similar configuration characteristics, making two “zone maps” which can be superimposed for a richer view of the entire space. We suppose the space to be the dominant variable, differentiated by light, because buildings are, first and foremost, physical objects which must be navigated to serve their primary purpose. Light can direct within a building, but it is not, in itself, the reason for a space's existence.

One can imagine a number of hypothetical situations in which the idea of light-syntax zone becomes easy to understand. For example, one could imagine a cafeteria that is a large open room lit at certain point by skylights from above. Controlling for thermal discomfort, it is reasonable to suppose that people might choose to sit in the circles of daylight directly below the skylights. This is a skylit/open light-syntax zone, while the darker areas around it are shadowed/open. The same skylight in a hallway would produce a different zone because though the light is the same, the space is much tighter (and possibly more highly occupied if the hallway is an axis of integration between several different spaces.) An occupant's behavior is first shaped by the space and then possibly directed by light. Daylight can provide differentiation in large spaces which otherwise have extremely similar values of integration across the entire room.

The proposed light-syntax types are found below in figure 3, with those present in the case study in bold. Here we take three very basic lighting conditions – next to a shaded window, next to an unshaded window, and away from the window – and juxtapose them with three basic space types – a secluded space (less integrated), an open space (more integrated), and a junction space which connects several other spaces (most integrated yet.)

	Space type			
Light type		*Shaded boundary*	*Unshaded boundary*	*Central*
	Secluded	Secluded/shaded boundary	**Secluded/unshaded boundary**	**Secluded/central**
	Open	**Open/shaded boundary**	Open/unshaded boundary	**Open/central**
	Junction	**Junction/shaded boundary**	Junction/unshaded boundary	**Junction/central**

Figure 3. Proposed light-syntax types present in the case study, which may be generalized to other spaces. Those in bold are present in the case study.

4 Case study

To test the concept of distinct light-syntax zones and develop a workflow for identifying these zones, a case study was performed on a daylit space with a changing flow of occupants. The methodology, results, and analysis will be each presented separately for the simulation study, experimental study, and statistical study which unites the two, which is then followed by a discussion of the findings.

4.1 Space selection

Several spaces on the EPFL campus were considered for the case study. The decision criteria for an acceptable space were:

- a variety of daylight conditions, both direct and indirect
- a variety of spatial conditions, both open and secluded
- freedom of movement for occupants
- in use throughout the day
- used for more than one activity (i.e. studying or eating)
- small enough for a single observer to take frequent, accurate observations

Based on these criteria, the cafe on the first floor of the SG building, the Cafe Giacometti, was selected. Photographs of the interior are shown in figure 4 below.

Figure 4. The central space of the cafe and the secluded space behind the counter.

Both direct and indirect lighting are found in the cafe – direct in the southwest corner, where a large unshaded window allows sunlight to fall on the tables and indirect in the rest of the highly-glazed space – as well both an open and less open space. The views from each of these windows are roughly analagous, as one looks out on the BM laboratory building and one looks out of the SV laboratory building.

The cafe is open between 8:00 AM until 4:00 PM or 6:00 PM, depending on the part of the year, allowing for observations to be made under varying light conditions. The cafe is a relatively compact space and generally has 83 seats, as well as three standing tables, shown in the plan in figure 5. The cafe is located in a classroom building largely dedicated to architecture and urbanism courses. It is frequented by a mix of students and campus employees for coffee breaks, socializing, business meetings, and lunch.

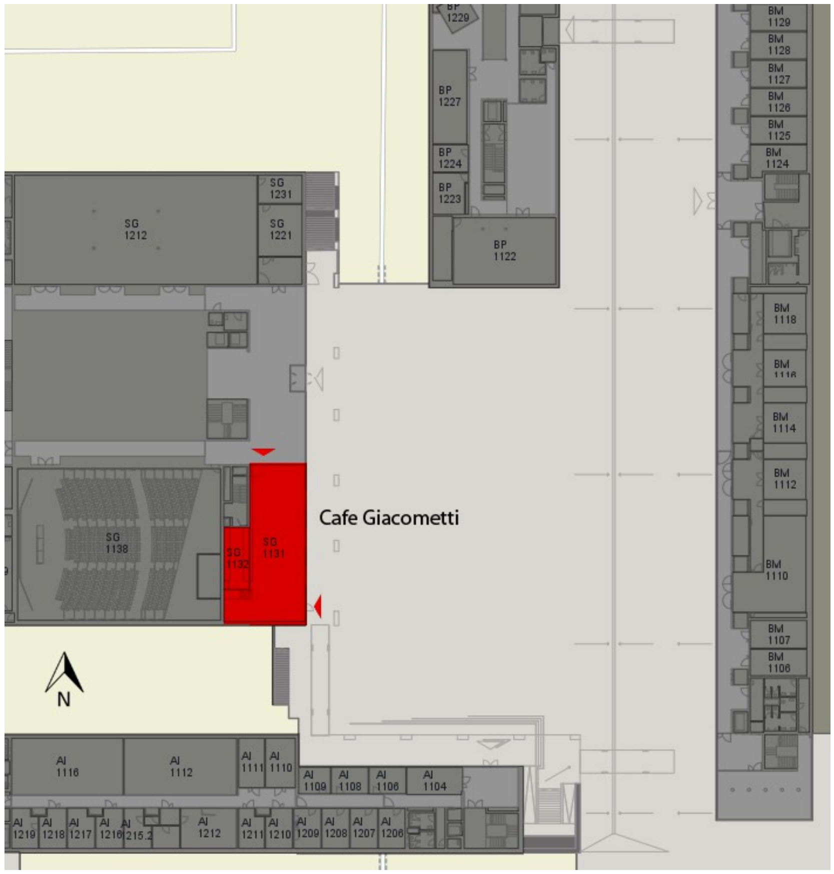


Figure 5. Plan of the Giacometti and its immediate surroundings in the SG classroom building. Points where the cafe opens to outside spaces are marked with red arrows. The southeast door only opens outward and so is not used as an entrance. The cafe faces onto a large courtyard area with additional seating.

The Giacometti was also seen as ideal because the electric lighting is usually turned off during the day in the summer months due to the copious quantities of daylight, making simulations of the interaction of artificial and natural light unnecessary.

4.2 Simulation study: zone definition

To define the light-syntax zones present in this cafe space, the daylight and spatial qualities were simulated.

4.2.1. Methodology

The Giacometti was analyzed using daylight simulations. The horizontal illuminance at workplane level was chosen because of its widespread acceptance in architectural practice and the relative speed with which it may be simulated.

In future studies, a metric which takes into account the whole perceived environment – for example, average luminance – may be used to develop more new light-syntax zone definitions with a stronger directional component. The issue of choosing appropriate metrics for defining light-syntax zones is discussed further in section 4.2.

A horizontal yearly illuminance profile was generated with a five-minute timestep, using the Ecotect/Radiance/Daysim package, as horizontal lighting levels are important to many study tasks. The weather profile for Geneva from the Energy Plus website was used in Daysim [27]. The simulation grid was set just above the height of the tables, with a resolution of 60 east-to-west by 80 north-to-south grid blocks. Because the bulk of the observations were planned for the months of May and June, these two months were separated out from the rest of the annual profile. At Lausanne's relatively high latitude, the variation between summer and winter lighting conditions is significant enough to obscure patterns that are unique to each of these periods through averaging.

Luminance images were simulated using Desktop Radiance to identify any unique lighting conditions, particularly direct light on tables, which might influence cafe users' choice of seating. However, for the time period observed, changes in occupancy rates seemed more closely linked to scheduling effects, i.e. mealtimes, than changes in the light condition, and so information about occupancy rates was used to determine the scheduling blocks in section 3.3.2.

DepthMap 10, a software produced by the Bartlett group University College London, was used to calculate the spatial syntax characteristics of the space, particularly physical connectivity and visual integration. For this space, the visual integration was calculated with a radius of 2, as this is the maximum depth of any space in the cafe from any other space. The grid size was set at a chair width – roughly 45 cm, judged to be roughly the amount of space an occupant takes up sitting or standing.

4.2.2. Results

To avoid information being lost to averaging effects, the illuminance data for May and June was split into three time segments throughout the day – from 8 AM to 12 PM, 12 PM to 4 PM, and from 4 PM to 8 PM – shown below in figure 6.

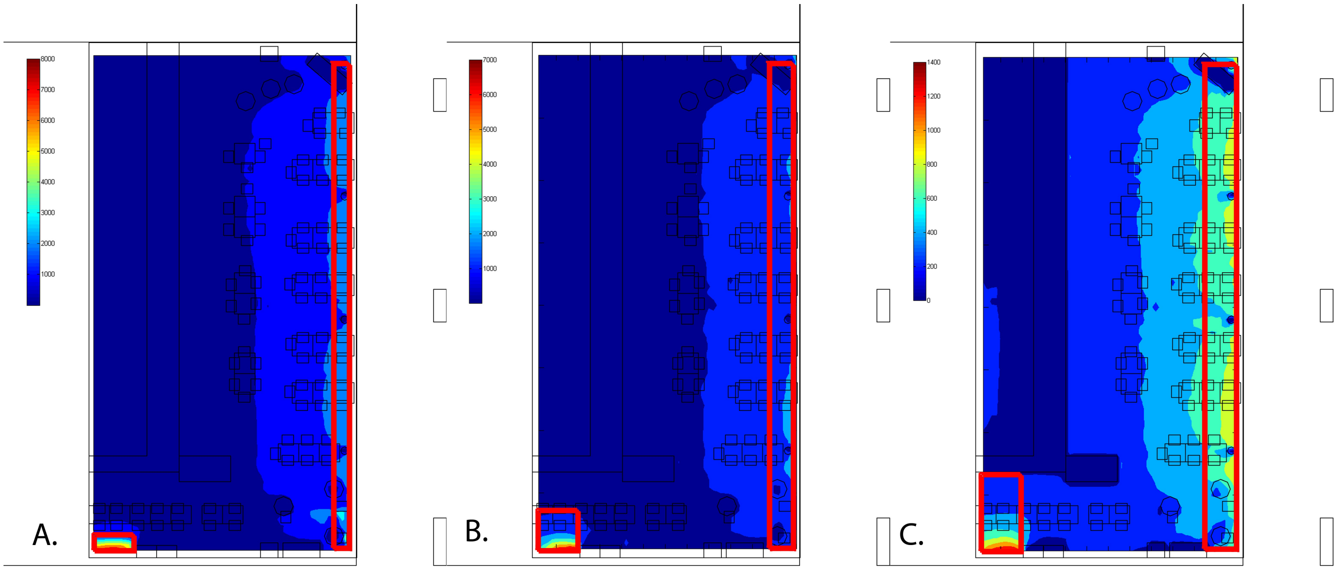


Figure 6. Average simulated illuminance for the months of May and June in the cafe between the hours of A. 8 AM to 12 PM B. 12 PM to 4 PM and C. 4 PM and 8 PM. Proposed window light zones are outlined in red.

During each of these periods of the day, the maximum and minimum illuminance varies in the central part of the cafe and the small secluded area in the southwest corner. In the morning, the area closest to the eastern glazing peaks at almost 3000 lux and drops to about 1000 lux near the counter. By contrast, the unshaded window on the south results in a patch of 7000 lux, though near the wall it drops to about 500 lux. The maximum in the central area is closer to 2000 lux during the afternoon hours and 800 lux in the evening, while the secluded southwestern area still gets 6500 lux near the window in the afternoon and 1500 in the evening.

Though the maximum and average horizontal illuminance vary significantly by time of day, the relative spatial illuminance variation remains roughly consistent. These variations are distinct between the area adjacent to the shaded glazing (the largest part of the cafe) and the area adjacent to the unshaded glazing (the secluded area in the southwest corner.) A section cut through the center of each glazing during the morning hours gives the image shown in figure 7.

While the maximum and minimum illuminance varied widely between the hours of 8 AM to 8 PM, the overall pattern of illuminance change as distance increased from the window stayed quite similar. Each slice through the cafe's illuminance profile correlates to the time periods graphed in figure 6. Based on these graphs, the “window zone” both in the shaded and unshaded condition seems logically to extend only about one meter from from the window – i.e. to the point in the graph where the slope of the illuminance line changes sharply to become less steep. These inflection points are circled in red on figure 7 and drawn in a hard red line in figure 6.

The change in gradient is used rather than the illuminance to define the light-syntax zones for two reasons. One, this allows different parts of the day to be directly compared. Two, light is typically perceived relatively rather than absolutely – a surface is bright in comparison to a surface next to it. However, even when comparing the gradient, it remains the case that the lighting zones change slightly throughout the day.

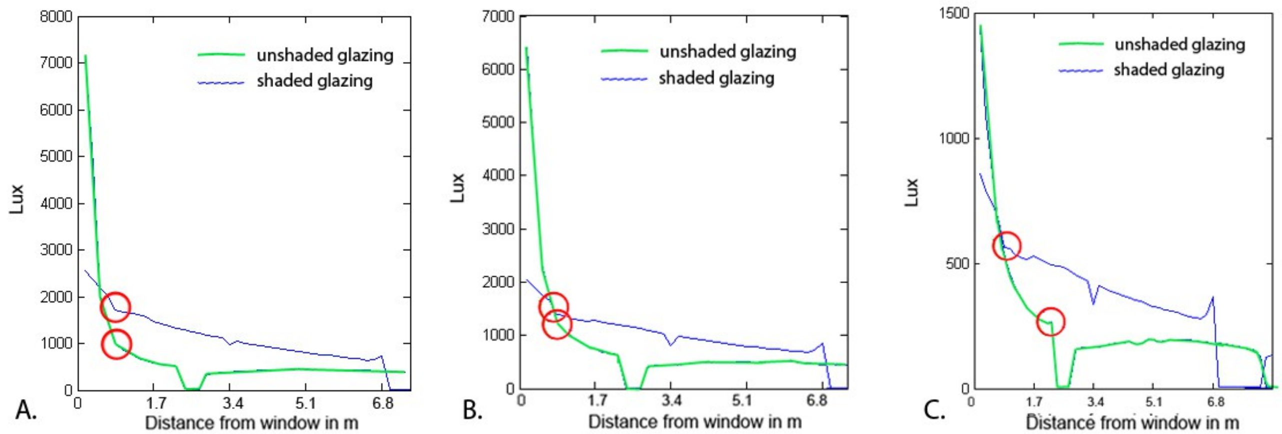


Figure 7. Rate of change in illuminance as distance from the window increases for A. 8 AM to 12 PM B. 12 PM to 4 PM and C. 4 PM and 8 PM. Changes in inflection are circled in red.

The values of several space syntax metrics were assessed using a plan of the space in Depthmap 10. The grid was set to correspond to the width of one person, so each square is roughly the space of one occupant in the space.

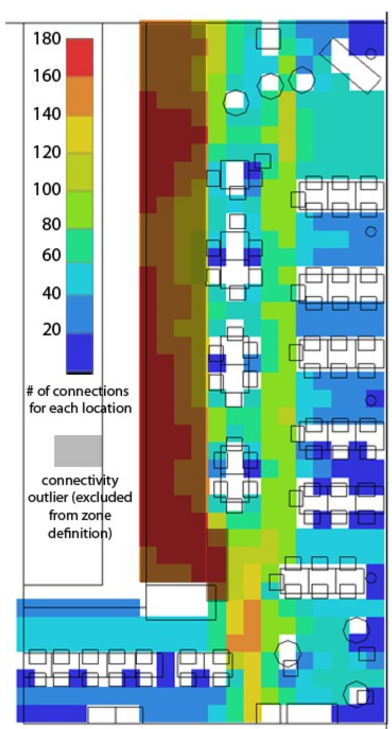


Figure 8. Physical connectivity within the space, given in number of straight-line connections between grid squares.

Though it seems, based on previous research, that visual integration is likely more important than physical connectivity in a situation where there is a lot of furniture present in an interior, the physical connectivity was assessed first with the furniture in the plan. This led to the identification of a zone next to the counter with a much higher physical connectivity than the rest of the cafe, which is roughly consistent, as shown in figure 5 below. Preliminary observation in the space also found that this is a high-traffic zone that is very often only occupied for only a minute or two by people who buy food in the cafe and then leave. These two factors were used to discard the counter zone from further analysis.

In figure 8, the physical connectivity is shown, with the discarded counter zone overlaid in gray. In general the seats in the southwestern secluded area and those along the eastern glazing have similar physical connectivity values that are lower than those in the southeastern corner and around the aisle seats.

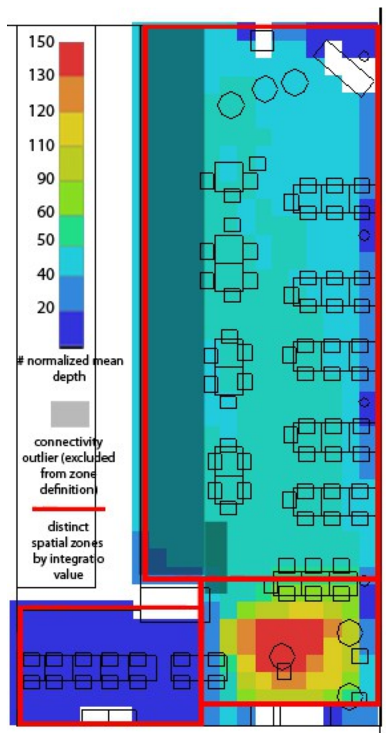
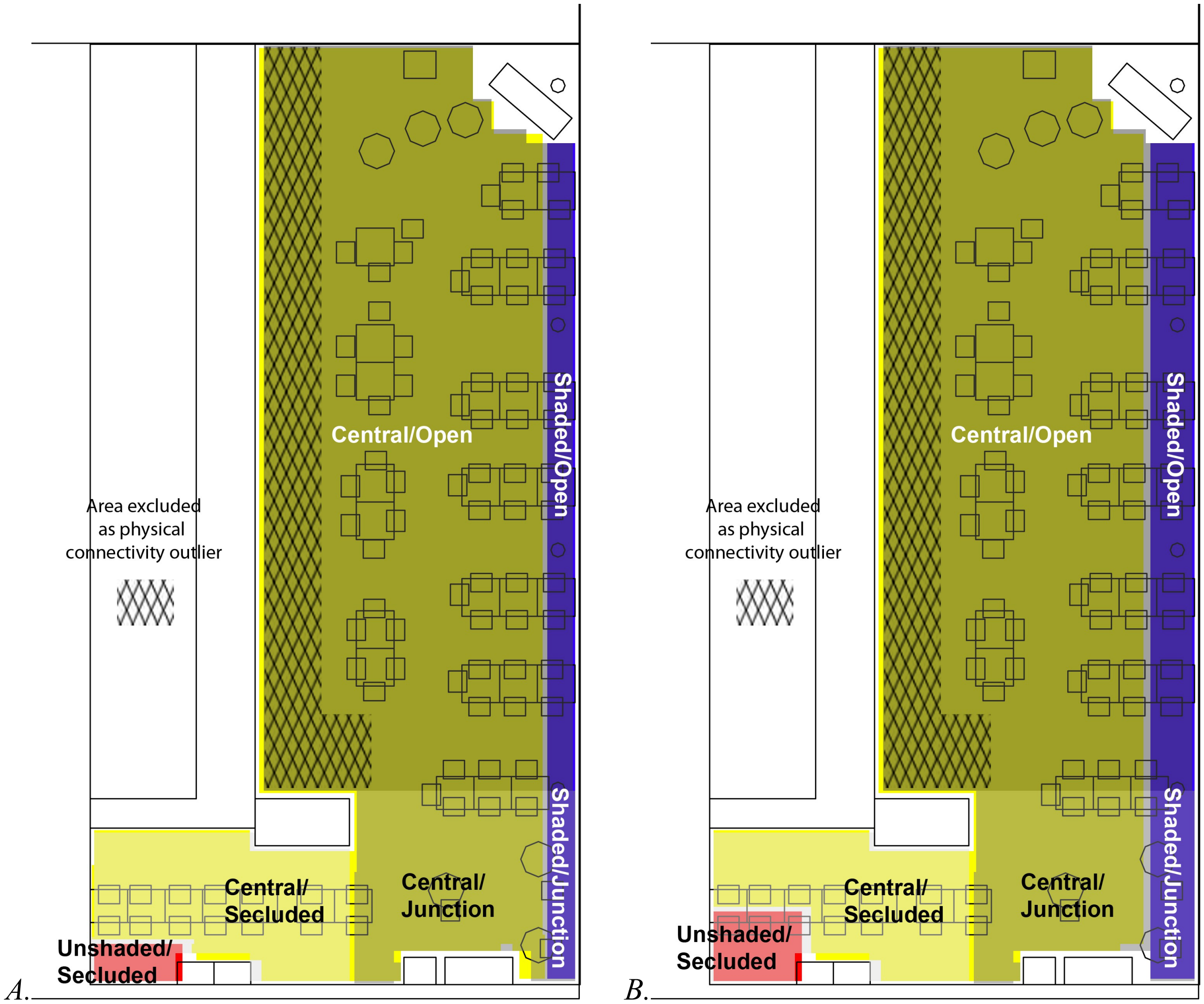


Figure 9. Visual integration, radius 2, within the space. Separate zones based on integration are outlined in red.

The visual integration values of the space, shown in figure 9, allow for a quick division into three spaces. The “secluded” portion of the space in the southwest corner has integration values between 9 and 19; the “junction area” has the highest visual integration, with values between 95 and 250; the “open area” has a medium and consistent level of integration across the space, ranging between 30 and 70 but averaging at about 50. Conveniently these thresholds produce three rectangular spatial zones.

By superimposing the light zones derived from horizontal illuminance found in figures 6 and 7 on the syntax zones derived from visual integration found in figure 9, we arrive at the theoretical division of the Giacommeti into six light-syntax zones, shown by scheduling block in figure 10. Because of the variations in light between the morning and later in the day, the zones gradually change shape. The window zones (shaded/open, shaded/junction, and unshaded/secluded) become larger as the day goes on and the inflection point moves deeper into the cafe.


Area excluded
as physical
connectivity outlier
Central/Open
Shaded/Open
Shaded/Junction
Central/
Junction
Central/
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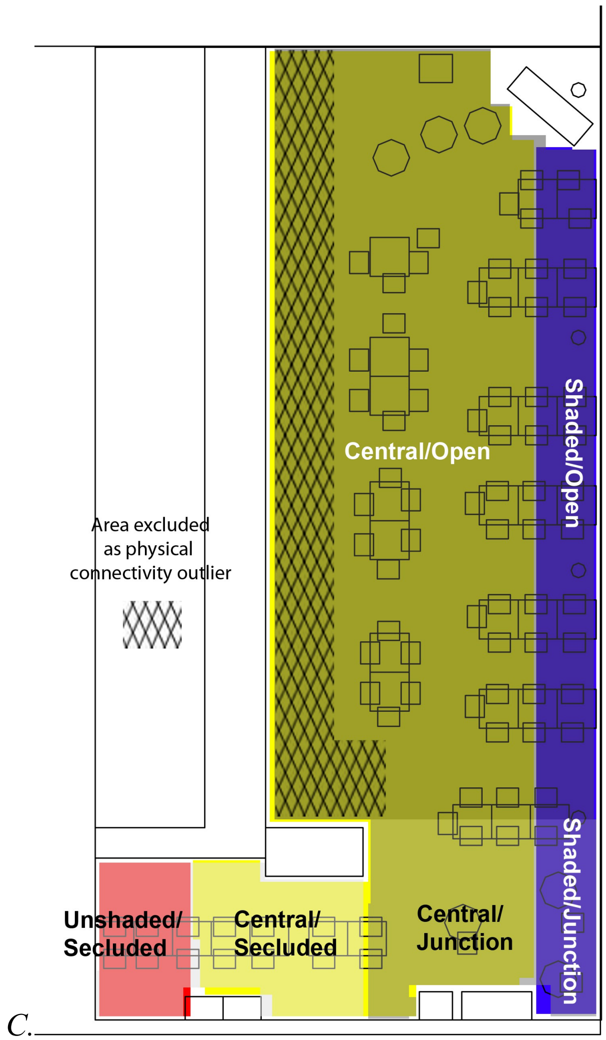


Figure 10. Hybrid light-syntax zones for morning, midday, and afternoon.

4.3 Experimental study: zone validation

To validate that the proposed zones show significantly different occupancy characteristics, an observational experiment was performed.

<u>4.3.1. Methodology</u>

An observation study was done to support the hypothesis that different parts of the cafe are preferentially used for certain activities in a manner which is correlated to their respective distinct spatial and light characteristics. By collecting data about how the seats in each of these zones are used – when, how often, and for what activity – the light-syntax zones proposed in section 3.2 may be supported or altered appropriately.

To make taking observations quick and easy, floor plans were printed with the standard seating places pre-marked. At five-minute intervals the occupied seats in the cafe were marked on the plan with an initial. These initials were each associated with a certain support – laptop, phone, papers, or food, or if the individual was engaged in talking at that moment. These observations were taken between the hours of 10:00 AM to 12:00 PM and between 1:00 PM and 5:00 PM. Observations were not taken during the noon hour. This choice was made due to practical considerations and because of previous experience in the cafe, which suggested it would be too crowded to accurately note all the occupied seating places.

Observations were done on a total of sixteen days in May, June, and July for a total of 73 hours. A matrix of the dates and hours observed is shown in the appendix. Each of the six daylit hours analyzed was observed on at least ten different days and no more than fourteen different days.

During this time period, the position of tables and chairs remained quite static. While occasionally a chair would be moved from one table to another, these transitory seats usually did not appear for more than a few timesteps on a single day. Chairs typically remained within the same light-syntax zone and so did not alter the overall occupancy. With this in mind, the seat changes were noted when they occurred, but not considered in the final analysis.

Sky type was determined to be important inasmuch as direct or diffuse natural light was present in the cafe. With this in mind, the inside of the cafe and the view to the exterior were photographed at every five-minute step. This information was compared against sky photos from the archives of panorama.epfl.ch, a resource which records a 360-degree view of the sky at ten-minutes intervals throughout the day, to assign a “light condition” to each hour of observation and the timesteps contained therein. These conditions were: (1) direct light present in the view field of the cafe occupants; (2) light rapidly changing between direct and diffuse; (3) diffuse light present. If the sky image from panorma.epfl.ch showed an obviously clear or overcast sky for the hour concerned, the light condition was automatically assigned as (1) or (3) respectively. However, in most cases the sky was an intermediate sky with both clouds and clear patches. In this case, the photos for each time step were consulted. If clear, dark shadows with sharp edges were clearly visible on the ground, the light condition was assigned as (1). If no shadows were visible on the ground, the light condition was assigned as (3). If there were multiple fluctuations within a single hour or the shadow type was indeterminate, the light condition was assigned as (2).

Examples of the three “light conditions” and their corresponding sky types are given below in figure 11.

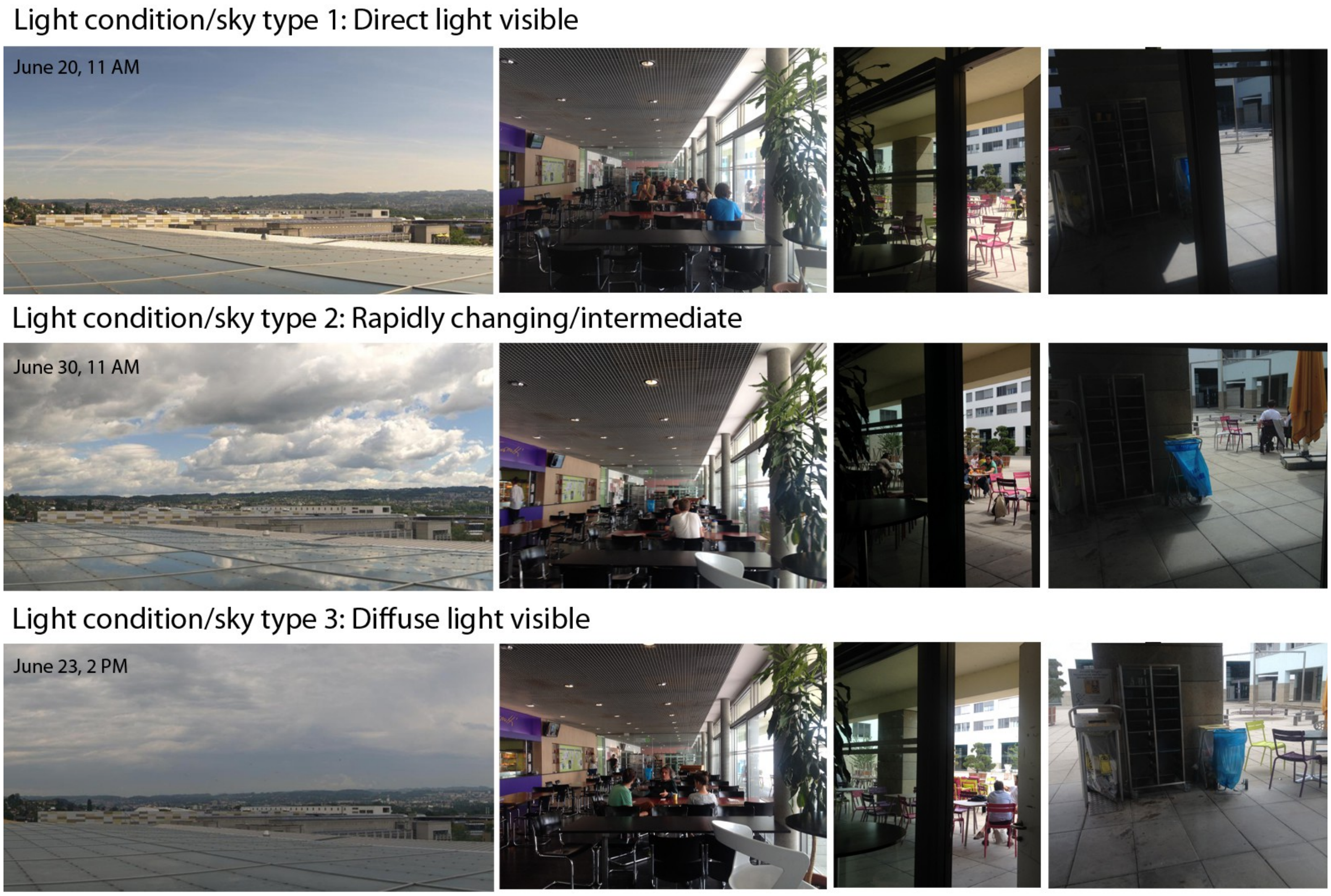


Figure 11. Sample days showing the three light conditions and their corresponding sky type.

The occupancy rate, OR_{tot}, was calculated with the following formula:

$$OR_{tot} = \text{total 5-minute timesteps occupied during observation/total 5-minute timesteps observed}$$

The independent and dependent variables in the observation experiment are shown below in figure X.

Independent variables	*Possible values*	*Dependent variables*	*Possible valuIes*
Light condition	Diffuse, direct, changing	Seat occupancy	Empty or filled
Spatial zone	Central, junction, secluded		
Scheduling	Morning, midday, afternoon		

Figure 12. Independent and dependent variables in observation experiment.

4.3.2. Results

The highest occupancy rate (OR_{tot}) observed was 0.3157, corresponding to a seat which was occupied for 21 hours, 50 minutes of the 73 observed, and the lowest 0.0012, corresponding to a seat which was occupied for five minutes of the total observed. The mode occupancy is 0.013, corresponding to 55 minutes occupied for the whole observation period.

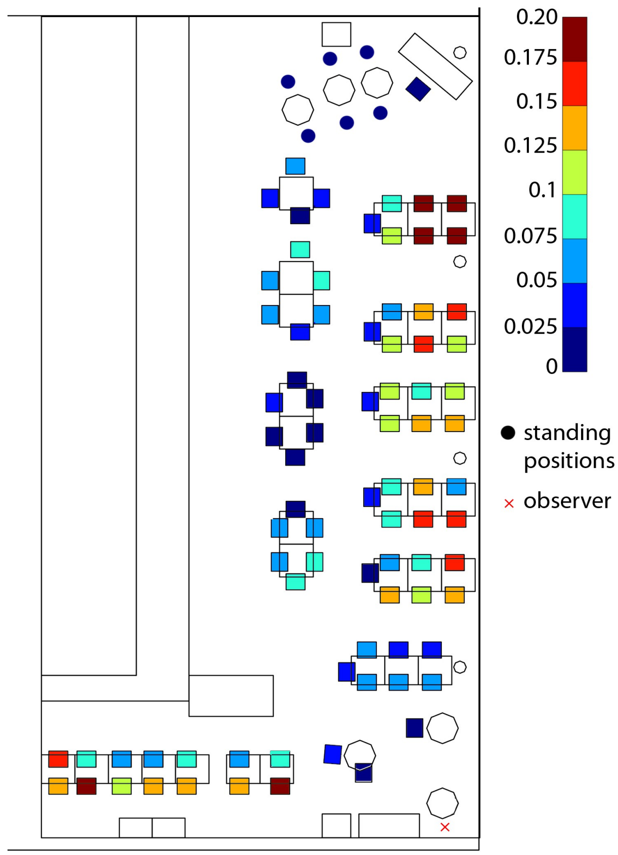


Figure 13. Occupancy (E) heat map for the whole period observed.

The spatial distribution of the occupancy is shown above in figure X. Overall, the most popular seats were found in the northeast corner near the window and in the southwest corner facing away from the window. In general, the seats close to the glazed wall on the east were more highly occupied. The least popular seats were those neighboring the aisle next to the food counter and the path to the outside door.

4.4 Statistical study

The simulation data and observation data was paired in a statistical study.

<u>4.4.1. Methodology</u>

Two primary methods were used to join the simulation data, both spatial and light, to the observation experiment data: correlation between the occupancy rate, OR, and the simulated illuminance and syntax data, and analysis of variance.

For the correlations involving simulated data, the appropriate value – integration, physical connectivity, or illuminance averaged over the appropriate time period – was taken from the grid point closest to the seat location. In the case of the spatial syntax data, when more than one grid square bordered a seat, the values of of all bordering grid squares were averaged together.

For the analysis of variance, the occupancy rate was calculated in a slightly different way. In this case, the following formula was used for hourly occupancy per seat:

$$OR_h = \textit{total 5-minute timesteps occupied during hour/total 5-minute timesteps observed during hour}$$

The ANOVA analysis was done first with the continuous simulated values (illuminance, integration, and connectivity) binned into four evenly spaced buckets, to check for a gradual falling off of occupancy rather than a sharp division between zones, and then binned into the proposed zones.

4.4.2. Results

The results for the statistical study are given as the impact of the three major independent variables on occupancy – scheduling, spatial syntax/configuration characteristics, and light condition – before examining the support for hybrid light-syntax zones.

4.4.2.1. Scheduling

Scheduling appeared to have a noticeable effect on the patterns of occupation in the cafe and so was examined further.

To discern the impact of scheduling effects, the observations were split into three groups. The cafe generally sees a group of people who come in only to socialize and have a coffee in the mid-morning and a rush of people eating around noon. The afternoon is mostly occupied by students working alone or in groups. Thus, based on the observations, the 1.5 hours from 10:00 AM to 11:30 AM was regarding as the “morning” observation block (18 five-minute timesteps), the half-hour from 11:30 AM to 12:00 PM and the hour from 1:00 PM to 2:00 PM as the “midday” observation block (18 five-minute timesteps), and the three-hour block from 2:00 PM to 5:00 PM as the “afternoon” block (36 five-minute timesteps.) With these groupings, the highest average occupancy is for the midday hours, of 0.107, followed by the morning hours, with a ratio of 0.095, and finally the afternoon, with 0.087.

When broken down into blocks by scheduling, the spatial picture of occupancy also changes somewhat, as shown in figure 14 below.

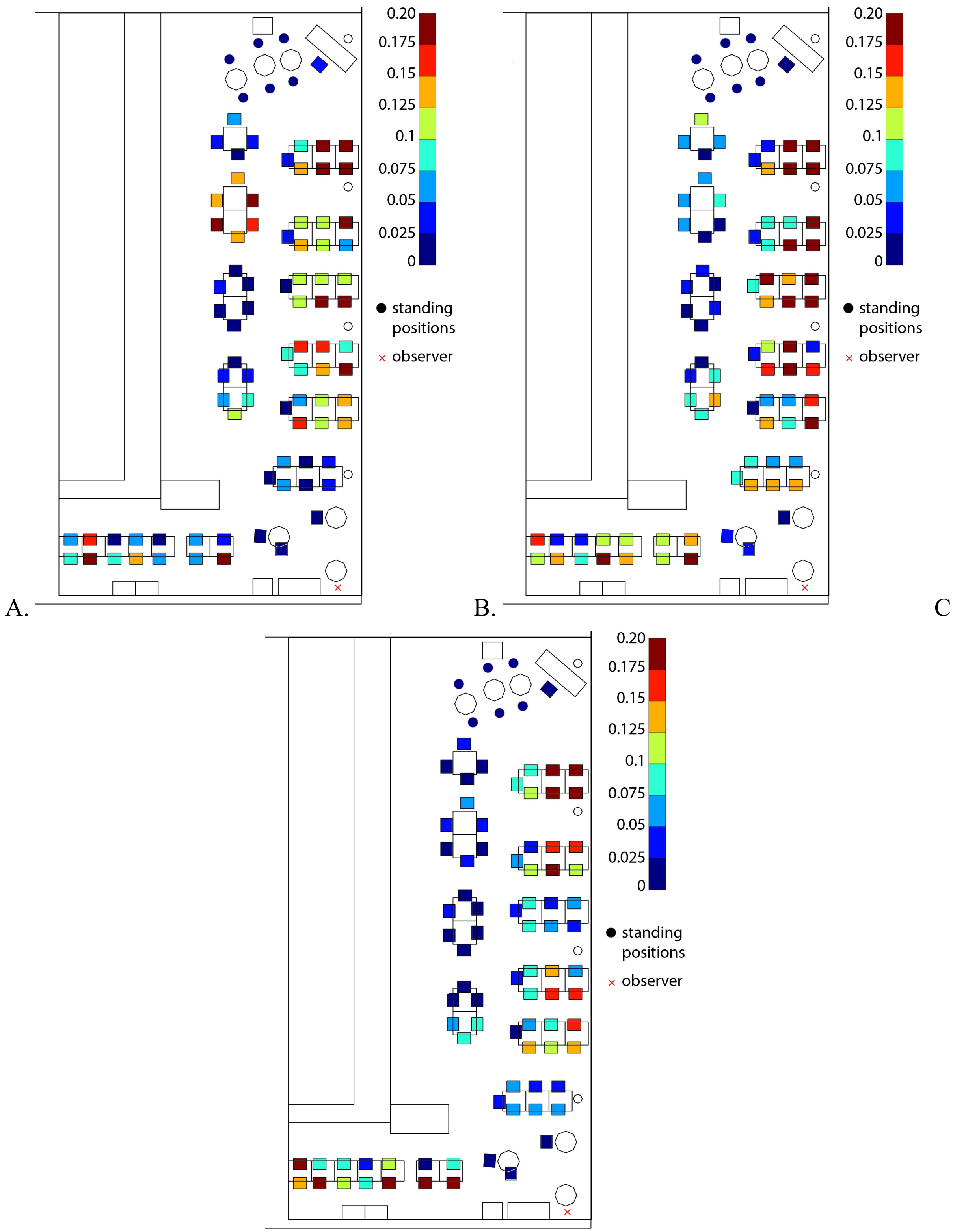


Figure 14. Occupancy (OR_{tot}) heat map for A. morning observation block B. midday observation block C. afternoon observation block.

During the morning schedule block, the southwest area of the cafe was less favored, and occupancy became more evenly spread across the large central space. Notably, two of the aisle tables become more popular. The small group of seats in the southeast corner remained unpopular, however. During the midday hours, the spatial distribution of occupancy is quite similar to that of the cafe over the entire observation period, only with elevated occupancy rates at all seats in the tables pushed against the east window. In the afternoon block, the aisle seats are more or less completely deserted, while the secluded area is highly favored.

During all schedule blocks, the standing tables near the entrance of the cafe were rarely used.

Despite the appearance of significance, when the calculated occupancy rates per seat for each of these scheduling blocks were compared against each other using ANOVA, they were not found to be significantly different, with a p value of 0.5292. This is shown in figure 14 below – while there is considerable variation between the scheduling blocks regarding the occupancy of the junction, it is the smallest section with the fewest number of seats and has little impact on the total occupancy, which varies little.

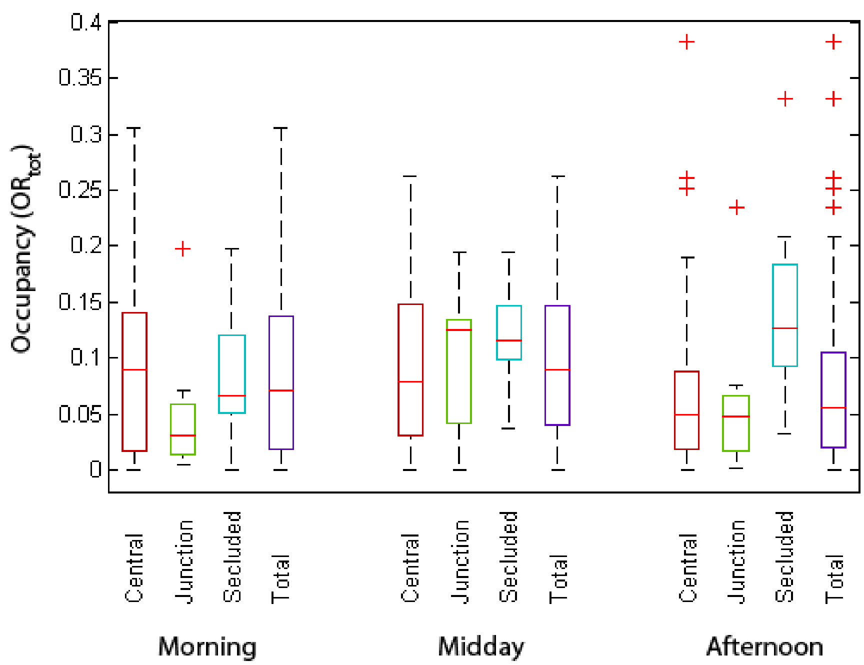


Figure 15. Boxplot of occupancy rate split by scheduling block and spatial zone.

4.4.2.2. Space syntax

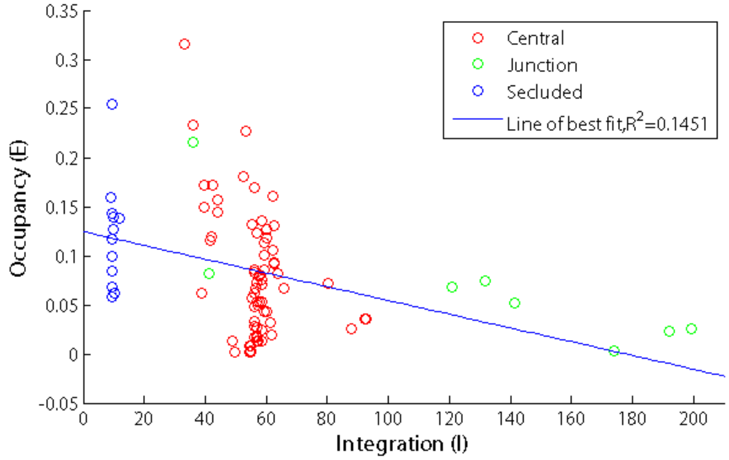


Figure 16. Occupancy ratio, OR_{tot}, (E in this chart) plotted against visual integration, radius 2, throughout the entire observed period. A slight negative correlation is observed between integration and occupancy.

The visual integration has a slight negative correlation with the overall occupancy rate per seat. The secluded and central areas tend to cluster together on the graph shown in figure 16 above, with a large range of occupancy rates seen for a single integration value. The line of best fit has a fairly low R^2 value, however, and in fact overall occupancy is more closely correlated with the physical connectivity of each seat, as shown in figure 17 below.

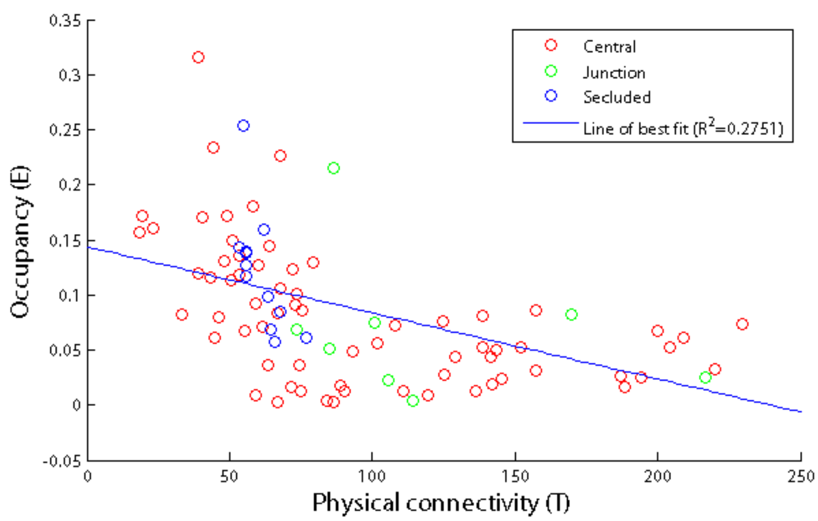


Figure 17. Occupancy ratio, OR_{tot}, (E in this chart) plotted against physical connectivity, T (number of physically unimpeded straight-line connections to the remaining 45 cm x 45 cm squares in the space.)

Here there is a stronger negative correlation between connectivity and occupancy rates – the seats that are least connected tend to be more highly occupied. When split into scheduling blocks, the correlation is weaker for the afternoon block (R^2=0.2247) and higher for the morning block (R^2=0.3140.)

4.4.2.3. Illuminance and light condition

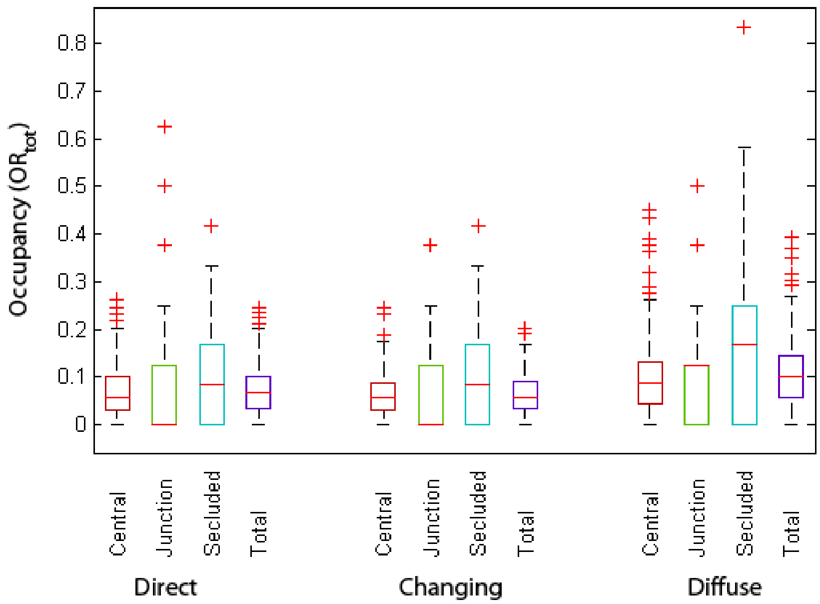
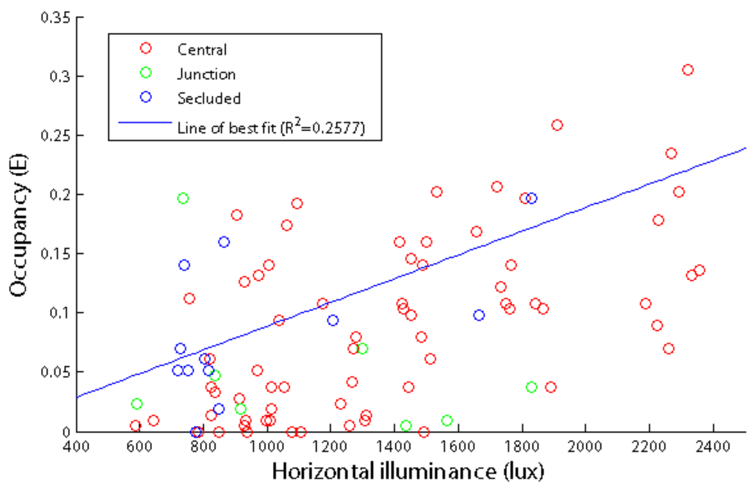


Figure 18. Box plot of overall occupancy rate split by light condition and space type.

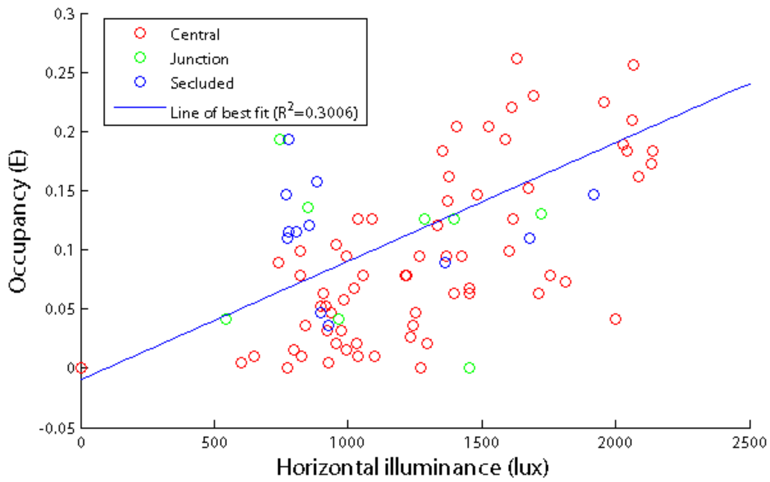
Splitting the observation data by light type shows that the cafe's overall occupancy rate is highest when diffuse light is present – that is, under consistently overcast skies. Diffuse light also seems to produce the most variance in occupancy rates compared to direct and changing light, as the data points for each of the space types stretch out far longer in this sky type.

Regardless of sky type, the "secluded" spatial zone is consistently the most highly occupied. However, this group also has the highest variance in occupancy rates, while the central group is more consistently occupied, at a ratio just below 0.1.

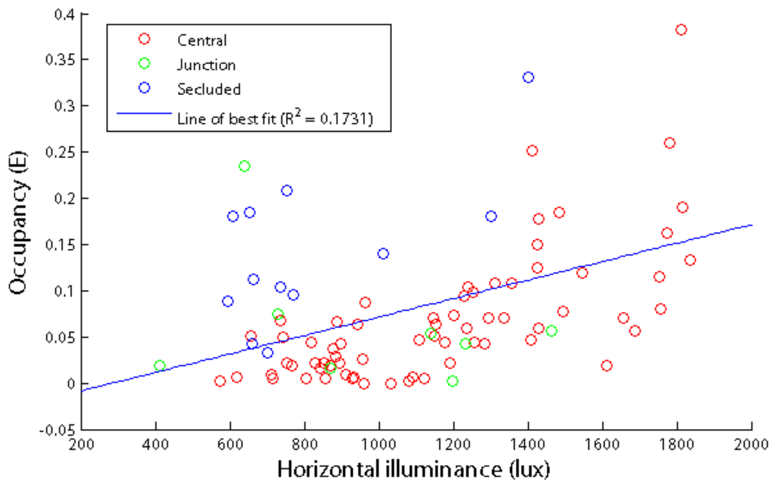
4.4.2.4. Light-syntax zones



A.



B.



C.

Figure 19. Horizontal illuminance (lux) plotted against average occupancy (E in this chart), with spatial groups highlighted. A. Average morning illuminance at each seat position against morning occupancy rate. B. Average midday illuminance against midday occupancy rate. C. Afternoon illuminance against afternoon occupancy rate.

There is a noticeable positive correlation between average illuminance at each seat position and the occupancy rate, shown in figure 19 above. When broken into scheduling blocks, the strongest correlation between illuminance and occupancy is found in the midday hours, with an R^2 value of 0.3006. The afternoon has the most modest correlation, with an R^2 value of 0.1731. When looking at only the seats in the central spatial area during the midday hours, the correlation between illuminance and occupancy improves to 0.4765.

In this space, the seating that is least-well connected – i.e. the seats closest to the window – are also the seats which are best-illuminated. Is relatively higher correlation of occupancy with illuminance just due to the correlation of connectivity and illuminance? To answer this question, connectivity was also plotted against illuminance per seat and lines of best fit calculated, and indeed, for all scheduling blocks connectivity and illuminance had a higher correlation than either respectively had with occupancy. The results are shown in figure 20 below.

The conclusion that connectivity is the key factor is not definite, however – in the midday scheduling block and overall, the correlation between illuminance and occupancy is higher than the correlation between connectivity and occupancy.

	Occupancy/Connectivity	Occupancy/Illuminance	Connectivity/Illuminance
Morning	0.3140	0.2577	0.3231
Midday	0.2255	0.3006	0.3555
Afternoon	0.2247	0.1731	0.2901
Total	0.2751	0.2939	0.3102

Figure 20. Table of R^2 values for occupancy rate vs. physical connectivity, occupancy rate vs. illuminance, and connectivity vs. illuminance during the morning, midday, and afternoon scheduling blocks, and overall.

The ANOVA results were largely inconclusive. The light condition (direct light, changing, or diffuse light) was highly significant in most tests ($p<0.05$.) However, when the interactions of the binned illuminances, integration, and connectivity were tested, they confounded each other and produced no result. Light condition and simulated illuminance had a significant interaction, but as these are not truly independent variables this seems questionable. Visual integration and physical connectivity had a significant interaction, however, and as they are calculated from different plans (one without furniture and one with) it seems possible that this interaction is legitimate.

When assigned to the zones set out in section 3.2.2, all the variables (zones based on syntax, zones based on light) were all shown to be significant, but when calculated with interactions the variables confounded and no result was produced.

4.5 Discussion

The observation experiment provided several surprisingly contradictory or inconclusive pieces of data. First, the fact that scheduling is not a significant factor in the occupancy rate seems particularly counterintuitive for a cafe which has a lunch rush lasting 1-2.5 hours. It's possible that because there were a disproportionate number of sunny mornings during the observation period (the direct light visible condition), the occupancy there is being unfairly represented as lower than it should be. Otherwise the light conditions were fairly evenly distributed across the observation set.

The sky type was the most significant single variable when tested in combination with the illuminance, physical connectivity, and visual integration variables, but there is unfortunately an explanation for this that does not mean that the zones are occupied differently based on exterior lighting conditions. In fact, when looking at figure 17, it becomes evident that the overall occupancy is much higher on diffuse light condition days – probably due to weather conditions. The cafe tends to empty out into the neighboring courtyard when it is sunny. The difference in occupancy patterns between light conditions is not because occupants are preferentially choosing to sit by the window when that zone is better-defined, but because the much higher ratio of occupants on diffuse light condition days (overcast skies) forces them to occupy even less-desirable seats, such as the aisle seats. This study cannot support the secondary hypothesis that occupancy patterns reflect exterior light conditions, even if it does not disprove it.

The first surprise of the case study is that the simulated integration values per seat do not show a position correlation with occupancy rate in the cafe, and in fact shows very little correlation with occupancy rate at all. Physical connectivity is a much stronger negative correlation – the less-well-connected a space is, the higher the occupancy is likely to be – which suggests that people using this cafe space are deliberately seeking out the most private spaces instead of picking the first seat available, as the integration model might suggest. It is worth noting that many previous studies finding a high correlation between integration and population density were done in urban settings, where individuals are not seeking a spot to sit for an extended period, but simply a route [4].

However, separating the seats by integration, as was done in figure 9, does seem to hold some merit. The correlation between visual integration and occupancy is quite weak, but figure 15 shows a very distinct grouping of the secluded, central, and junction seats. When tested against sky type by itself using ANOVA, without taking into consideration physical connectivity or simulated illuminance, the spatial grouping proposed is significant. The fact that visual integration and physical connectivity have an interaction in the full-factor ANOVA suggests that perhaps occupants preferentially choose certain zones over each other (secluded is favored over central is favored over junction), but once they have picked a zone, they choose the least well-connected seat available within that zone.

Because illuminance is so well-correlated with physical connectivity, its effect on the occupancy is far more uncertain. Certainly, occupants seem to seek out regions of high illuminance – but is that because they prefer more light, or more privacy? It would be necessary to observe a space with relatively large populations of poorly-connected seats of various lighting conditions, both with a great deal of illuminance and without.

The one small factor in favor of illuminance having a unique effect on occupancy rates is that, as shown in figure 19, during the midday scheduling block and overall, illuminance is slightly better correlated with occupancy than physical connectivity is. This suggests it does not owe its effect entirely to its correlation with connectivity in the space.

5 Limitations and future work

Numerous issues presented themselves during the progress of this thesis. Many of these issues are interesting research questions which could lead to further projects and, hopefully, continued development of hybrid light-syntax zones as a prediction tool for indoor occupancy.

5.1 Issues with space and scheduling

The hypothesis given at the beginning of this thesis did not predict the importance of physical connectivity – mostly determined by furniture placement in this space – to the choices of occupants in positioning themselves. While the the proposed syntax zones based on visual integration and the proposed lighting zones based on horizontal illuminance lay mostly at right angles with one another, providing distinct areas of intersection, the regions of similar physical connectivity and similar horizontal illuminance more or less coincided. Areas of high horizontal illuminance were also areas of low physical connectivity, both of which seemed to be a strong draw for cafe users, and it was very difficult to tease apart the effect of the two.

The space also proved statistically difficult to work with because the three proposed spatial zones based on visual integration did not have similar numbers of seats, causing some sample size effects.

It is also possible that external scheduling caused unrepresentative fluctuations in the cafe occupancy. The observation period overlapped the end of the spring term, a short vacation period, the spring exam session, and the longer summer vacation period. It seems very likely that at this particular moment there was an outflow of one population – the architecture students who frequent the building and its studios – and the re-establishment of another – summer researchers and employees enjoying the lack of students during the summer holidays. Probably these two groups exhibit different behavior and occupancy patterns that were not accounted for in this study.

Finally, the impact of weather on occupancy cannot be clarified from a short study in only one portion of the year. The relative distribution of clear days (represented by the “direct light present” light condition in the observation study) and cloudy days (representing by the “diffuse light present” light condition) was not even for all the schedule blocks – the mornings were disproportionately sunny, while the afternoons were disproportionately overcast. Weather's other consequences – such as air temperature, wind speed, and threat of precipitation – were not examined, though they doubtless had an impact on the choice of occupants to sit outside in the courtyard or inside the cafe.

5.2 Appropriate metrics

The issue of choosing appropriate metrics to define the hybrid light-syntax zones was one of great concern. The horizontal illuminance profile seems appropriate for a space where studying is a frequent activity and paper supports are often used on the work plane. However, the vertical component of perceived light is very important. Other proposed metrics include average luminance and vertical illuminance.

Also considered in the study were combined new, less-well-validated metrics that might give some sense of directionality in the space. DepthMap10 generates maps for “isovist drift angle” and “isovist drift magnitude,” which give, respectively, the angular displacement from the physical center of a single convex space and the distance to the physical center of a single convex space [28]. Paired with a light metric which derives a “contrast drift angle” and a “contrast drift magnitude,” for example, from luminance images of the space, it may be possible to determine not only the spatial directionality of an indoor area but also the light directionality.

One example of such a metric is given in figure 20 – two “available contrast” maps calculated from the Michelson contrast, $(I_{max} – I_{min})/(I_{max} – I_{min})$, where I_{max} is the maximum luminance and I_{min} in the minimum luminance available in the viewfield [29]. In this sample case, the contrast available to the viewer is highest when they are sitting in the aisle seats either facing north or south and in the secluded seats facing north. This metric suggests a different pattern of behavior than the horizontal illuminance metric which may be worth investigating.

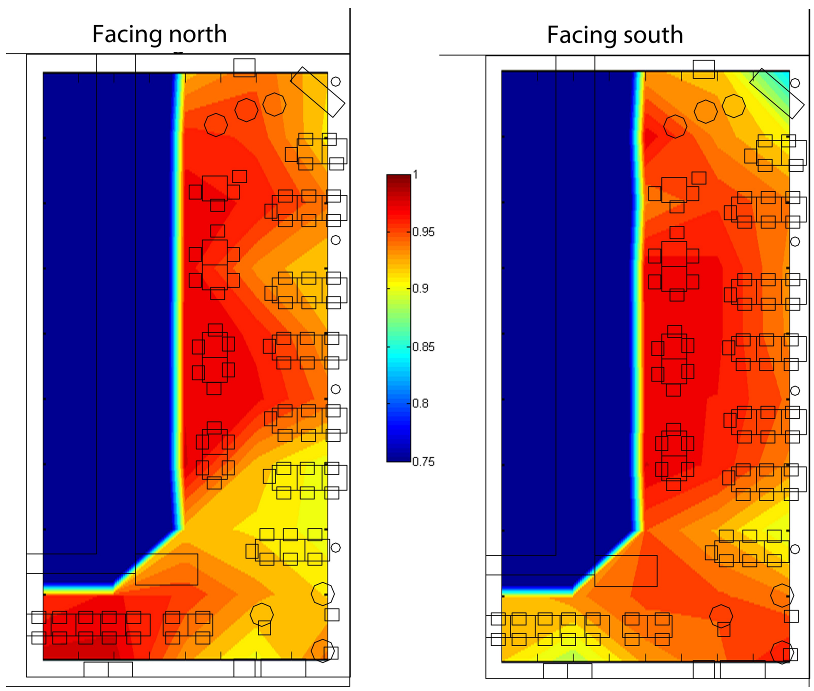


Figure 21. A possible future lighting metric – available contrast, calculated with the Michelson contrast formula, when facing a given view direction. The sample day simulated is May 19 at 9 AM.

5.3 Next steps

In the space examined, the analysis could be continued with several steps. First, though the seating in the cafe remained mostly static, occasionally an occupant would move a chair from one table to another or stay standing behind another occupant's chair for several timesteps, effectively creating a new position. In this report's analysis, these extra, transitory seats were disregarded, as they typically are short-lived and the chair is promptly moved back to its former position. However, for a full picture of the occupancy of the cafe, a model should be developed which accounts for moving seats and standing occupants.

Information was also collected about the activity supports used by each occupant. However, this information was not analyzed to determine if certain supports were more or less likely to be found in certain light-syntax zones.

The zone definition with regards to light and the correlations developed in the analysis are both based on simulations in this report. It would be useful to validate these daylight profiles with lux measurements carried out in the space. These real-life measurements could be used to tailor the zone boundaries and the correlations appropriately.

While the above tasks could enrich the analysis of the Giacometti cafe test case, the validation and refinement of the light-syntax zone concept requires test cases in several other spaces where the physical connectivity and illuminance profile are not so tightly linked. It would also be useful to choose a space in which the highly-occupied seats are more evenly split with regards to view direction, so the impact of this factor can be examined.

As noted in the limitations of this study, a year-round study would be helpful to account for a wider variety of lighting and weather conditions.

6 Conclusions

This thesis proposed a novel model for understanding occupancy and seat choice in daylit public spaces: hybrid light-syntax zones. These zones are defined using both data about the illuminance profile and spatial syntax characteristics such as visual integration and physical connectivity. With more development these zones could possibly be useful tool for predicting relative occupancies of different sections of public indoor spaces and, eventually, for as a tool for design.

While the case study in the Giacometti did not definitively validate the light-syntax zone concept by showing a strong interaction between the illuminance and configuration variables, it arguably did not invalidate the concept as a method of understanding and predicting occupancy rates in architectural spaces. It provided support for a negative correlation between physical connectivity and occupancy rates. Moreover, it suggested that segmenting a space by visual integration values is a useful way to identify parts of a public indoor area with significantly different occupancy rates. The impact of light remains less sure because areas of high illuminance in the cafe overlap almost perfectly with areas of low physical connectivity. While exterior light condition has a significant effect on occupancy rates, it cannot be put down with certainty to the response of occupants to light – or to the weather.

The case study also provided valuable information about what characteristics are important to select the next space to test against the light-syntax zone model. It suggested which syntax metrics are likely to be more or less useful for what level of analysis. Hopefully the questions raised in this thesis about the interactions of light and space and their effects on building occupants become a new and fruitful area of inquiry.

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Appendix

Workflow, diagrammed.