4.430 Daylighting Project

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PHASE I: ANALYSIS

General Description

The CSAIL Recreation Area is lies on the fourth floor, in roughly the northwest quadrant of the Stata Center designed by Frank F. Gehry. Daylight enters the room through three windows, one centered on each of the South, East and West walls. The room is completely open to an access corridor running East West along the northern edge of the space. The three windows open into an interior atrium enclosed by a glass skylight over the fourth floor. At no point does the space have direct access to the exterior of the building.

Sketch of building and floor plan of fourth floor
removed due to copyright restrictions.

The area's furniture consists of a table tennis table and a foosball table, both directly related to the area's primary recreation activities. Deep windows with spacious sills adequate for sitting also suggested a secondary reading/study activity. Thus, measurement procedures sought to gather evidence that would appropriately critique the location and availability of daylight for an individual to engage in these activities.

The area has three primary surface treatments. The walls and ceilings are painted matte white, the floors are covered with dark blue carpeting, and the 2 columns are exposed concrete. The two playing surfaces are both dark green in color that provides a dark background with which to better see the orange or white table tennis balls and pink foosball.

General Observations

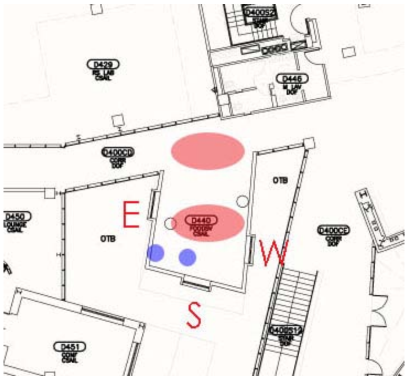


Figure 1: range of movement diagram

Numerous visits to the space at different times of day suggested the space was utilized for table tennis much more frequently than table tennis. Upon entering the area players would immediately turn on the ceiling lights if they were not already on. After playing several games of both table tennis and foosball we made the following observations. Table tennis requires significantly more space than foosball (figure 1). Without the supplement of electric lighting the space was too dark to effectively follow the ball and made these already demanding hand-eye coordination activities very difficult. Even supplementing the daylight with overhead lights the room seemed darker than ideal. Furthermore the eye seemed to relate much more to the ball than to its background surroundings. The space was rarely occupied during morning visits and seemed to see most of its use in the hours after lunch. As the Stata Center is primarily an academic building housing classroom, research and laboratory space, the recreational zone it seems reasonable to classify the recreational zone as a secondary space that sees very little morning use. The deep window sills initially thought to provide a cozy reading nook seemed to be employed primarily as a counter or shelf which visitors placed bookbags jackets on. The East sill was used to store table tennis balls and paddles.

Illuminance Recording Procedure

The recreational nature of the space suggested that the illumination of playing surfaces was of primary importance. Thus, both playing surfaces were divided into a grid and using a lux-mete, illuminance values were recorded at each point along the grids at the surface height of 34” (see figure 2). In addition, illumiinance values were recorded throughout the space at a height of 34” at each point along a 5’x5’ grid (see figure 3). This provided a general understanding of where daylight was most abundant in the area at the level of the playing surfaces.

Illuminance levels were also recorded at the surface of the wall and the floor. These measurements along with corresponding measurements of luminance were used to calculate the reflectivity of the wall ceiling and the carpet respectively.

Luminance Recording Procedure

Recognizing that the quality of light becomes most important only at specific points within the room (i.e. moments where hand-eye coordination is necessary, or reading is appropriate), a luminance meter and camera were used in tandem to calculate luminance values from the five positions most commonly taken up by the area’s users:

1. Ping-pong table facing the hallway
2. Ping-pong table facing the window
3. Foosball table facing the corner
4. Foosball table facing the window
5. Window sill/ Reading nook

A series of digital images using a gradation of exposures were taken from approximately eye level at each of these five positions. The camera was angled towards the playing surfaces to capture the range of vision necessary for the respective activities. Using the imaging software Photosphere these images were combined into a High Dynamic Range (HDR) image from each of the critical points (see figures 4-8). The images were calibrated using luminance readings taken from the corresponding points. Once calibrated using luminance recordings from the corresponding locations the HDR images provide luminance measurements from any point on the image. The variety of luminance readings from a single point allowed the assessment of specific locations of glare and high/low contrast apparent to a person engaging in the area's recreational activities.

Illuminance Analysis

Figure 2: Illuminance of playing surfaces

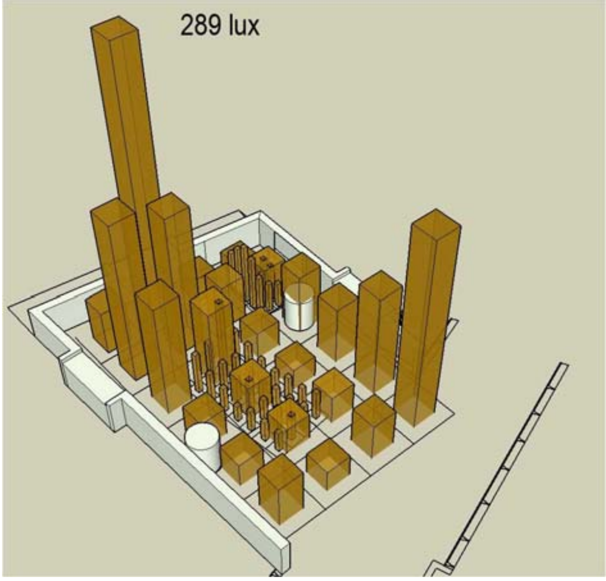


Figure 3: General illuminance of area

Based on the data recorded at 34" the majority of recreational zone falls under "insufficient illuminance" category. Most test loci return values that are below 50 lux, which is the minimum suggested illuminance for circulation/corridor space. Conditions near the windows are slightly better, reaching 289 lux at the South window, however, even these isolated spikes in illuminance levels are below the minimum value of 300 lux suggested for reading and writing. The "critical areas," namely around the foosball table and the ping-pong table are inadequately illuminated with values between 12-42 lux at the foosball table and 20-46 lux at the ping-pong table.

Luminance Analysis

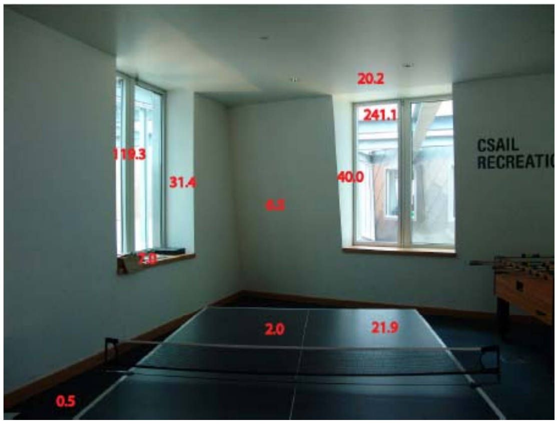


Figure 4: Table Tennis facing South

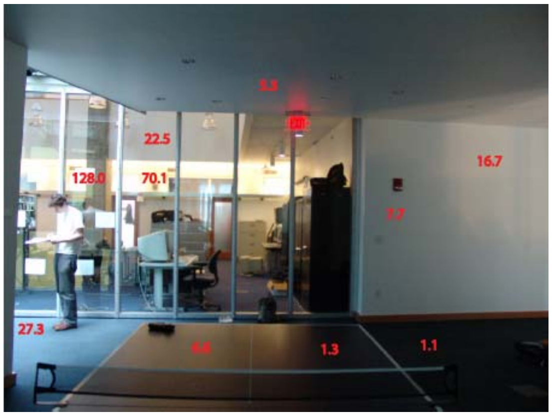


Figure 5: Table Tennis facing North

General observations coupled with luminance mappings from the five "critical areas" (figures 3-7) indicate that the South and East windows as well as the glazed surface of the North corridor are potential sources of glare to persons engaged in the associated recreational activities. Figure 3 indicates that contrast ratios on the order of 1:100 occur between objects beyond the South window and the playing surface. Ratios of 1:50 occur between the East Window and the playing surface. This data indicates points of glare in the visual field that are distracting and visually taxing for the player in this position. Although the visual field of the opposing player indicated in figure 4 does not offer a view to the outside, points of contrast between the table and bright white sheets of paper posted to the glazed wall result in contrast ratios upwards of 1:15. Furthermore activity in the office/lab beyond the glazed wall may distract the player.

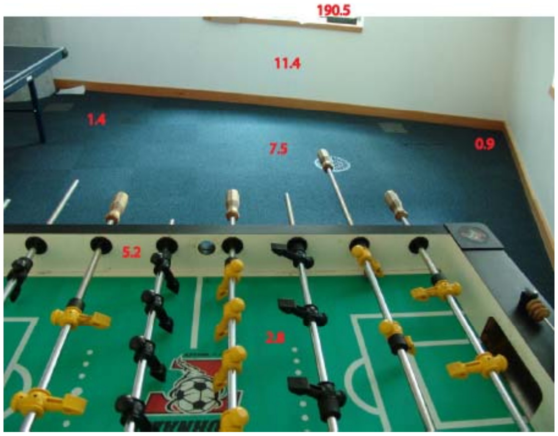


Figure 6: Foosball facing East

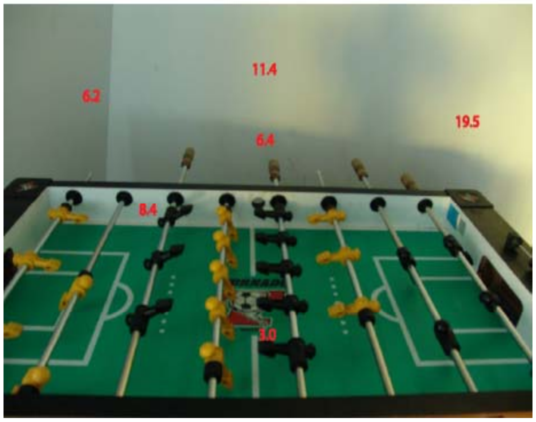
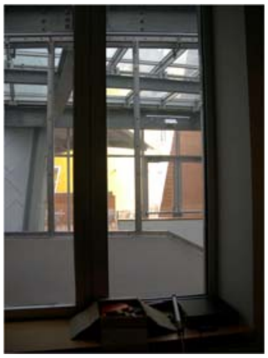


Figure 7: Foosball facing West



The luminance maps corresponding to foosball indicate a sharp contrast in the visual field of only one player. In figure 5 a contrast ratio of 1:100 occurs between the table surface and the building facades beyond the East window, specifically the yellow cone shown at right. The values in figure 6 do not indicate areas of high contrast that might be distracting or visually distracting giving this player a distinct advantage over his opponent.

A luminance map of the South window sill (figure 7) was also produced, however, observations indicated that the spaces were not being used for reading/studying. While the general illuminance is much higher than the gaming surfaces, reflections off the brushed aluminum window casing represent a source of high contrast and glare.

Figure 8: South window sill

Combining the luminance (L) illuminance (E) we calculated the reflection coefficients (ρ) the carpet, walls and ceilings using the formula $E=(L\pi)/\rho$. The average reflection coefficient for the carpet was calculated to be 0.09 while the walls and ceiling (both diffuse white surfaces) was calculated to be 0.70.

Stereographic Studies

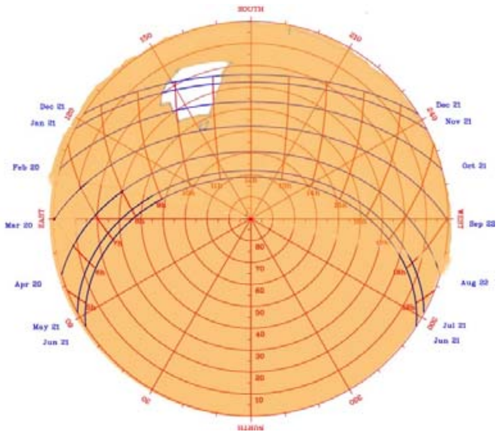


Figure 9: Stereographic chart of South window

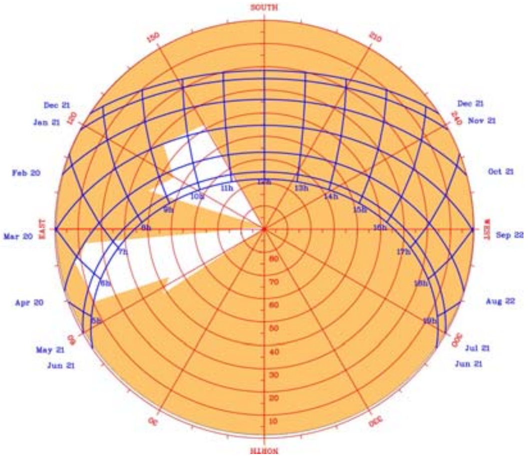


Figure 10: Stereographic chart of East window

Stereographic charts of the South and East windows were created to give an estimate of what time of day and year direct sunlight could be expected to penetrate the space. The charts also indicate what percentage of the sky is available to the window. The West window is flanked immediately by a wall rising five more stories blocking any direct sunlight. Both the East and West charts indicate that the only direct sunlight occurs before 11AM when the space is very rarely used. Furthermore since the windows open to an atrium space covered with a dense network of structural elements and glass mullions (see Fig 11) the access to sky from either window is significantly decreased.

Figure 11: Image illustrating sky access from east window

Conclusions

- The space is used primarily for table tennis in the afternoon and evening
- Table tennis requires a large range of motion
- Both table tennis and foosball require high levels of illumination and a contrast free backdrop free of distracting movement and glare
- The illuminance of the space is reasonably adequate (approaching 300lux) at the windows but quickly drops beyond the immediate window areas and is generally inadequate throughout the space.
- Luminance values are typically low from the five "critical areas" indicated
- High contrast and glare are a concern from the South and East windows as well as the glass wall on the Northern edge.
- Direct sunlight penetration occurs only in the morning hours
- None of the windows has access to a significant portion of the sky.

PHASE II: DIAGNOSTICS

Given the results of Phase I, the following recommendations were established for initial diagnosis of the space.

1. Increase illuminance levels both on and around the playing surfaces using daylight wherever possible, but to supplement any lacking daylight with appropriate electric light strategies..
2. Eliminate/Redirect potential glare on ceilings and walls.
3. Seek alternative lighter color for floor surfaces to reduce contrast to a 1:3 ratio.
4. Thermal issues not an issue

In order to more specifically address these issues, it was considered reasonable to consult standard lighting recommendations for both table tennis and foosball by official organizations of each sport. While foosball generally governed by a “house rules” philosophy of lighting as well as gameplay, the International Table Tennis Federation Regulations for International Competitions, Section 3.2.2 offered the following requirements for lighting:

> *3.2.3.3 The playing area shall be enclosed by surrounds about 75cm high, all of the same dark background colour, separating it from adjacent playing areas and from spectators.*
> *3.2.3.4 In World and Olympic title competitions the light intensity, measured at the height of the playing surface, shall be at least 1000 lux uniformly over the whole of the playing surface and at least 500 lux elsewhere in the playing area; in other competitions the intensity shall be at least 600 lux uniformly over the playing surface and at least 400 lux elsewhere in the playing area.*
> *3.2.3.5 Where several tables are in use, the lighting level shall be the same for all of them, and the level of background lighting in the playing hall shall not be greater than the lowest level in the playing area.*
> *3.2.3.6 The light source shall not be less than 5m above the floor.*
> *3.2.3.7 The background shall be generally dark and shall not contain bright light sources or daylight through uncovered windows or other apertures.*
> *3.2.3.8 The flooring shall not be light-coloured, brightly reflecting or slippery and its surface shall not be of brick, ceramics, concrete or stone; in World and Olympic title competitions the flooring shall be of wood or of a brand and type of rollable synthetic material authorised by the ITTF.*[1]

Due to the purposes of the project, and the recognition that this design is for recreation rather than competition, these regulations were used as a foundation on which to more adequately specify the initial diagnostic conclusions to the following, more defined recommendations:

1. **600 lux over the playing surfaces of both the table tennis and foosball tables, with 400 lux in the surrounding area, using daylight strategies wherever possible.** The numerical values for this goal come from directly from the ITTF Handbook, and although Article 3.2.3.7 indicates that no daylight should be utilized, for the purposes of the project and taking once again into account that this space is for recreation, it was determined that creative use of daylight (i.e. directing it to walls or ceiling rather than directly into the eyes of the players) should be attempted to obtain this quantitative goal while simultaneously daylight’s potential drawbacks and inconsistencies.
2. **Utilize electric lighting system to supplement any lacking daylight to achieve Goal #1.** Such lighting design would be operable and utilize dimmers as a means of supplementing or replacing daylight when the quantitative values stipulated in Article 3.2.3.4 and in Goal #1 could not be reached. This lighting would be energy efficient, and provide a smooth transition from available daylight to electric lighting systems. Although the Article 3.2.3.6 recommends that electric lights be 5m off the ground, once again for the purposes of this project and the

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[1] http://www.ittf.com/ITTF_Hand_Book/2006/ITTF%20Handbook%202006%20-%20Chapter%203.pdf

recognition that such accommodation would require major geometric (and probably unnecessary) renovations to the space, such conditions as previously stated would most likely be reasonable enough to accommodate recreation activity.

3. **Maintain dark color at floor level, seeking a contrast ratio of approximately 1:15.** Although originally considered a possible deterrent to the playing of table tennis, Article 3.2.3.7 recommends dark colored backgrounds, like the carpet already existing in the space. Further, after experiments with both table tennis and foosball, it was determined that a contrast ratio of 1:3 is probably too extreme, and for the purposes of the game and the movement of body and eye, a 1:15 contrast ratio was considerably more appropriate.
4. **Eliminate/Redirect potential glare occurring at hours of daylight after 12:00pm.** Given the academic nature and profession of those most likely utilizing the space, as well as observations illustrating what time the space is most often activated, it was considered reasonable to address the glare and direct daylight entering the space only after 12:00pm: the approximate time for lunch and the time after which students and faculty, as well as passersby will be willing to take breaks from the early morning work to engage in the activities of table tennis and foosball. Although it was determined that no direct daylight is entering the space in fact entering the space after morning hours, it was noticed that deterring glare is a problem due to the reflective nature of certain elements outside the space (Fig 12).

Figure 12: Glare from metallic surfaces outside space.

5. **Thermal issues not an issue.** Due to the spaces location and situation (i.e. no direct frontage to sky, no doors or isolating the space from surrounding areas) it was felt that any solar gains to the space would not only be extremely negligible, but would also be quickly mitigated by the existing HVAC system. Thus thermal issues for the space were deemed not necessary to address for the purposes of this project.

PHASE III-A: PROPOSAL

The following major strategies were proposed to meet the goals established by the diagnostics phase of the project:

- Interior Surface Treatment
- Fenestration Modification

Interior Surface Treatment

This strategy involves non-structural/construction modifications to the space, including color alterations, window treatments, and electric lighting conditions.

1. **Maintain the present colors and locations in the recreation area.** The existing conditions and coloring of the space should remain as is. The dark colored carpeting and surface areas provide the qualities stipulated in Articles 3.2.3.7-8 of the ITTF handbook. While this does not apply to the walls and ceilings of the space, it is determined that if the daylight enters such that it keeps the walls generally dark while the ceiling lit appropriately, the nature of the existing walls will be sufficient enough to cooperate with ITTF standards (Fig 13). It was also thought that perhaps the tables could be moved to alternative locations within the space, but given the size and movement necessary for each (particularly table tennis) it was deemed that the furniture should remain where it is and lighting work to accommodate the current locations.

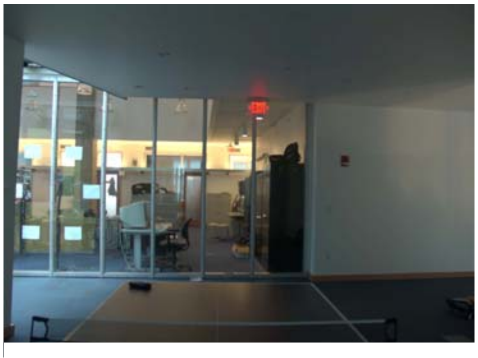

Figure 13: Existing Conditions

2. **Install translucent blinds at both the north glass wall and the east window (Fig 14).** Translucent blinds at these locations would serve to maintain human autonomy of the space, including establishing visibility to outside spaces and blocking glare while redirecting light, when such conditions are deemed desirable by those persons inhabiting the space. The blinds at the east window would eliminate the previously mentioned glare problem discussed in Goal #4. The blinds at the north wall would not only remove potential distraction from workers in the laboratories beyond, but also, when closed, would allow light from the west corridor to potentially wash into the back part of the space.

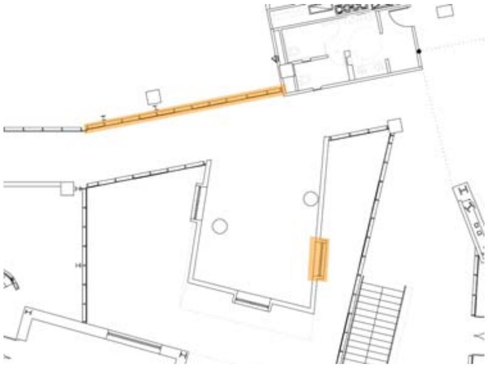

Figure 14: Translucent blind locations

3. **Improve the electric lighting at both tables and the surrounding areas.** The present lighting conditions of the space are random, dark and insufficient for the activities performed within the space. An alternative lighting system integrated with the daylighting strategies and focused more on said activities would greatly enhance the space's use. Such lighting would include compact fluorescent bulbs, which are energy saving, and dimmers, which would help limit the use of electricity and allow the daylight to be the primary use in the space (Fig 15).

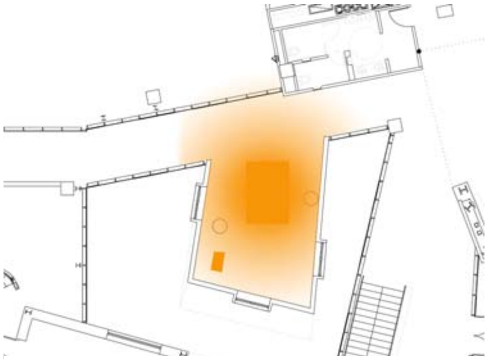

Figure 15: Electric lighting focus

Fenestration Modification

This major alteration to the space includes a light “scoop” based on an anidolic system, to be located at the south window (Fig 16). The south window is chosen due to the nature of such a lighting strategy and the location of the table tennis table, the primary activity taking place in the space. Further, the south window has greater access to diffuse light from the sky, while the east window has greater access to direct light, potentially contributing more glare than useful light.

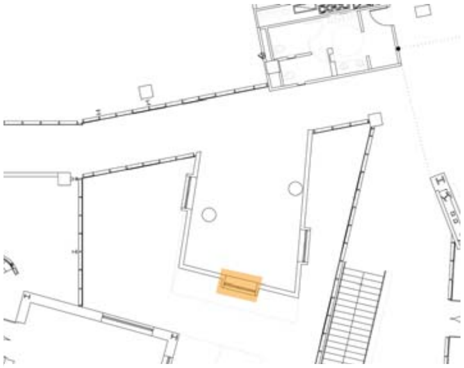

Figure 16: Location of light scoop

The light scoop combines the attributes of an anidolic system with that of a light shelf to create a system that best meets the needs of the space. The typical anidolic system uses three parabolic mirrors to gather light from the exterior and push it deep back into a given area. Its significant benefit is that instead of only redistributing exterior light, it amplifies it, causing more light to enter the room than normally achieved from a ordinary window. Its drawbacks, however, typically include that it is performs best when gathering only diffuse light, and thus should always face north. This is because it sends light in a parallel fashion from the window, resulting in any direct light to cause glare to anyone high enough to see into the mirrors themselves. A light shelf, while always directing light towards a ceiling, works best usually for direct light, and typically only for a small portion of the space. Given the nature of the spaces surrounding the window in question, the light scoop proposed will draw from both concepts in that it shall consist of only the one part of the anidolic that operates most like a light shelf. As a result, it gather both diffuse, and whatever available direct sunlight, and project that light onto the ceiling of the space, as well as pushing that light as far back into the room as possible (Fig 17-18).

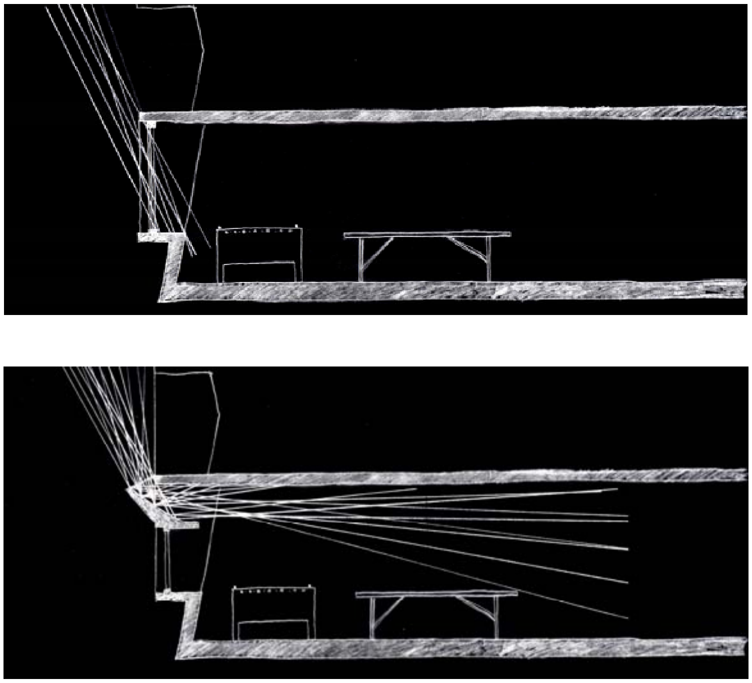

Figure 17-18: Ray-tracing sketches comparing light gathering of regular window to that of the proposed light scoop

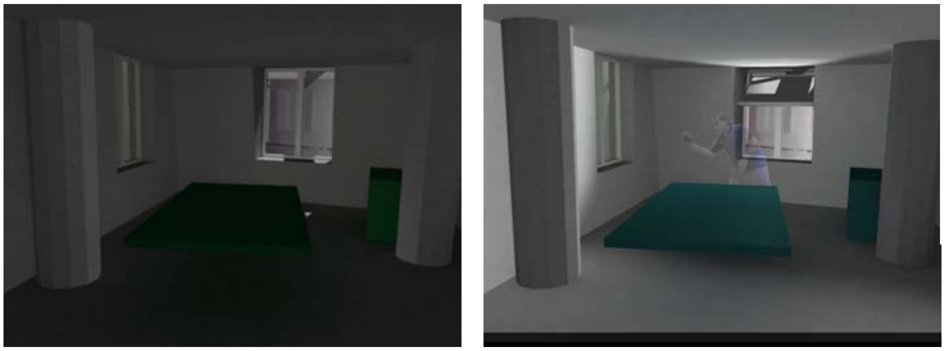

Figure 19-20: Lighting quality improvement to the space following light scoop installation.

The expected results of this procedure are thus:

- **Redirection of a larger portion of the exterior to the table tennis table specifically.** This will come out of the anidolic nature of the light scoop.
- **Signifcant illuminance increase on the ceiling.** This will come out of the light shelf nature of the scoop.
- **Architectural "blending-in" of the space.** This third issue is a by-product of the installation of the scoop. Typically anidolic systems are too large and cumbersome to fit into an area, however the heights of the windows in the given space are such that a lights scoop of significant size would not impede on the feel of the windows in question. The present windows have deep sills comfortable enough to sit on, and tall heights that run to the ceiling. A system installed in one of theses windows would actually enhance the quality and experience of "sitting on the sill" in the sense that it would be more appropriately scaled to one engaging in this activity, either to watch a table tennis match, or to sit and read. Inspiration for this idea comes from the Exeter Library designed by Louis Kahn, where reading carrels possess two types of windows – one for lighting the larger space of the library, and one for lighting the space of the individual (Fig 21).

Photograph removed due
to copyright restrictions.

Figure 21: Reading carrel, Exeter Library. (http://courses.arch.hku.hk/precedent/2001/Exeter_Library/photos/studycarrels1.jpg)

PHASE III-B: EVALUATION

The proposed system is evaluated in two ways: projected graphical analysis (qualitative method) and daylight factor calculation (quantitative method).

Qualitative Evaluation

As described in previous section, the light scoop system was proposed because it does not just redistribute light, but it actually amplifies the amount of light that is received by the space investigated. Figure 22 illustrates the amount of sky that the light scoop enables the room to be "exposed" to that otherwise would never be received by the interior of the space investigated.

Based on this qualitative analysis, it appears that the proposed system will in fact increase the daylighting in the space. However, a more rigorous hand calculation was done to quantify the amount of light increased and to evaluate if the improvement is sufficient and meets the targeted values.

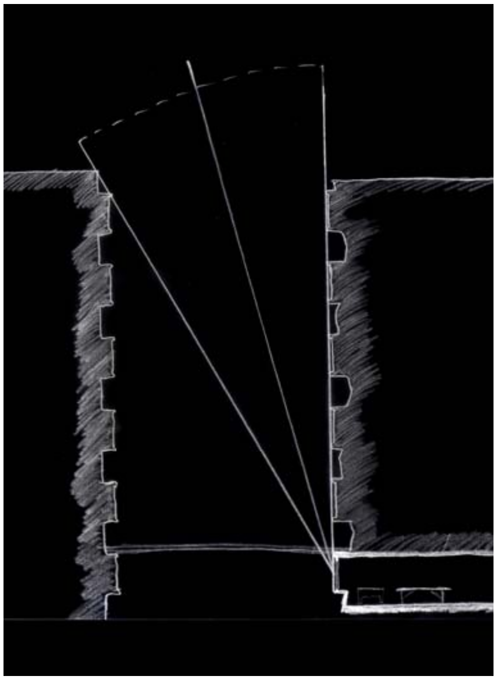

Figure 22: available light to scoop

Quantitative Evaluation

Daylight factors (**DF**) were calculated for existing conditions and for condition after the proposed system is installed. The chosen method for calculation is split-flux method and was carried out according to the protocol suggested by SquareOne. [2]

The split-flux method is done by calculating the flux in three distinct areas. This is based on the assumption that, ignoring direct sunlight, natural light reaches a point inside a building in three ways:

1. **Sky Component (SC)**
   This is light directly from the sky through an opening. In this investigation SC would be light directly from the windows. Note that this is NOT direct sunlight, but rather direct diffused light.
2. **Externally Reflected Component (ERC)**
   This is light reflected off the ground, trees or other buildings.
3. **Reflected Component (IRC)**
   This is the inter-reflection of SC and ERC off other surfaces within the room.

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[2] http://squ1.org/wiki/Split_Flux_Method

The reason behind the splitting of the light contributing areas is that each component affects the lighting condition inside the room differently. The resulting DF is expressed as a percentage and is the sum of the three components:

DF = SC + ERC + IRC

1. Sky Component (SC)

The Sky Component is determined using a Daylight Factor Protractor. The following Daylight Factor Protractor (fig. 23) is for CIE overcast sky and is for vertical glazing, therefore appropriate for this investigation.

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Figure 22: The three components of the split-flux method

Externally Reflected Component (ERC)

The Externally Reflected Component is determined in identical manner as the Sky Component. However, to more accurately simulate the lower light levels due to reflection off one or more surfaces, the final value is multiplied by a coefficient. The coefficient is usually 0.2, which is an average reflectance assumed for most normal building materials and natural surfaces. The value in the analysis of the space addressed in this project has been bumped up to 0.4 because the Stata Center's exterior façade is made of materials that mostly consist of brushed aluminum, which can reach a reflectivity coefficient as high as 0.7. But since the surrounding buildings are not all made out of this highly reflective material, the final 0.4 value is obtained through multiplying the 0.2 constant by two. This essentially is an assumption that the buildings surrounding the space investigated are twice as reflective as most normal buildings.
Given that the Stata Center is an unconventional building, this assumption is considered reasonable.

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Figure 23: Daylight Factor Protractor

Internally Reflected Component (IRC)

The Internally Reflected Component is calculated using the following equation. The equation considers the internal reflectance of different surfaces inside the space and the total area of windows.

$$IRC = \frac{0.85\,W}{A\,(1 - p_1)} \times (Cp_2 + 5p_3)$$

Where:

W = Total window area (m^2),
A = Total internal surface area, including walls, floors, ceilings and windows (m^2),
p_1 = Area weighted average reflectance of surfaces making up A, (use 0.1 as reflectance for glass).
p_2 = Average reflectance of surfaces below the height of the test point, usually a working plane of 600mm above the floor,
p_3 = Average reflectance of surfaces above the working plane, and
C = Coefficient of external obstruction

The followings figures are used for the calculation of the IRC of the space investigated, assumptions are noted wherever they were made:

$W = 9.3\ m^2$ $A = 195.1 m^2$

These were obtained by calculating the total window areas and the total internal surface areas using CAD. As a result, the accuracy of this calculating can be considered fairly high.

$p_1 = 0.445$ $p_2 = 0.20$ $p_3 = 0.60$

For the reflectance of the surfaces, the following figures were used:

Ceiling and walls: matte white walls that are NOT brand new, therefore the lower range of the reflectance coefficient of 0.7 is assigned for the ceiling and walls

*Floo*r: made of dark color carpet; the reflectance coefficient was found by calculation **p=Lπ/E**, where **p** is the reflectance coefficient, **L** is the luminance of the surface, and **E** is the illuminance of surface. A series of luminance and illuminance values were found using available instruments and the average reflectance coefficient was found to be 0.0938.

$C = 17$

The coefficient of external obstruction refers to the average height of all external obstructions. Because the surrounding buildings are of different heights, an “average” was taken by measuring the angles on site using a protractor. The average is found to be about 45 degrees. Using Table A, the coefficients of external obstruction, the value of **C** is determined to be about 17.

Table A - Coefficients of external obstruction (C)

0°	10°	20°	30°	40°	50°	60°	70°	80°
39	35	31	25	20	14	10	7	5

Since DF is location specific, 4 critical positions have been chosen where DF will be calculated and compared. The 4 loci are as shown in figure 24.

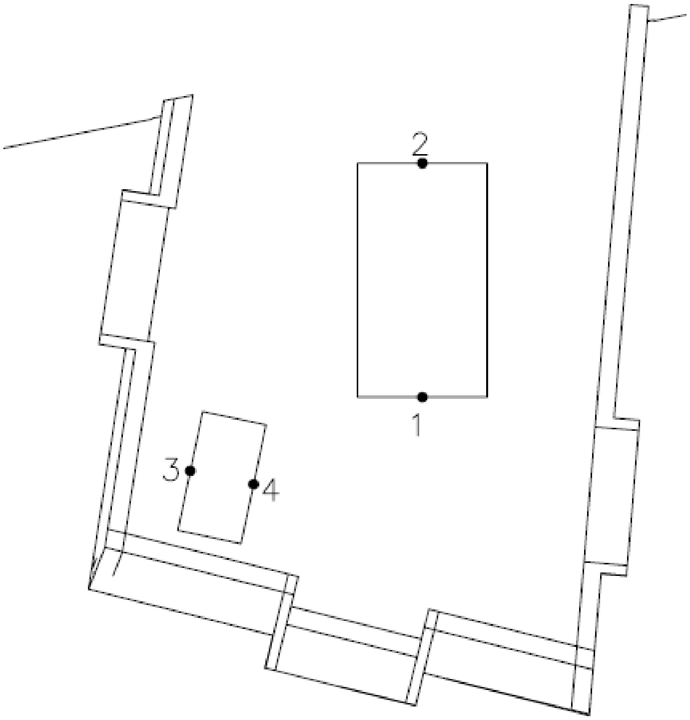

Figure 24: Four critical loci where DF is calculated

Using the method and assumption described above, the existing DF are found and are shown in Table B:

Table B

Locus	**Sky Component (SC)**				**Externally Reflected Component (ERC) Total*Avg.reflectance(0.4)**	**Internally Reflected Component (IRC)**	**Daylight Factor (DF) DF = SC + ERC + IRC**	**Correction Factor**	**Final DF**
	South	**West**	**East**	**Total**					
1	0.98	0.72	1.86	**3.56**	**1.42**	**0.47**	**5.45**	**0.33**	**1.80**
2	0.2	0.36	0.23	**0.79**	**0.32**	**0.47**	**1.58**	**0.33**	**0.52**
3	0.05	0.0	0.29	**0.34**	**0.14**	**0.47**	**0.95**	**0.33**	**0.31**
4	0.33	0.1	0.53	**0.96**	**0.38**	**0.47**	**1.81**	**0.33**	**0.60**

It should be noted that overcast sky condition is used because it is considered to be a worst case scenario. But although daylight factor account for the influence of the window size and position, interior surfaces properties, space geometry, it ignores orientation, weather, location, time, glare and overheating issues. It should also be noted that just by following the aforementioned process does not arrive at the DF of the space investigated because no where in the described method takes into account of the giant steel beams supporting the skylights that are blocking much of the sky. Therefore, a correction factor of 1.3 was used.

As shown, the DF is expressed as a percentage. Table C shows a very general relationship of the DF and their corresponding quality of daylighting. Although the percentage alone can be used as a comparative quantity, the illuminance of the 4 critical loci were found to obtain more specific numbers that will not only shed some light on how realistic the calculations are but also provide a baseline with which the targeted illuminance stated in the proposal part of this report can be compared.

Table C

Below 1% = unacceptable
2% = ok
4% = good[4]

The illuminance were obtained from the DF by using the equation

$$DF = E_{point\ inside}/E_{horizontal\ outside}$$

E horizontal outside is found to be 7600 lux using the Design Sky Calculator provided by SquareOne. (Figure 25)[5]

Image removed due to copyright restrictions.

Figure 25: Sky Illuminance Calculator, courtesy of Squareone.

The resultant illuminance are summarized in Table D:

Locus		E_h (lux)		$E_{p\text{-calculated}}$ (lux)		$E_{p\text{-measured}}$ (lux)
1		7600		**136.78632**		**50**
2		7600		**39.52608**		**30**
3		7600		**23.72568**		**27**
4		7600		**45.49512**		**60**

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[4] M. Andersen

[5] http://squ1.org/wiki/Sky_Illuminance

Included in the table are the values measured with a luxmeter. As shown by the table, except at locus 1, the calculated values at the other locations are relatively close to the measured values. This demonstrates that the assumptions made in the split-flux method were reasonable and the same method can be applied to evaluate the proposed system and the comparison of the existing and altered conditions can be made.

The calculation procedure for the proposed system was identical to the one used for existing condition, except the values were calculated in two parts: 1) the light received from without the aid of the light scoop system (2) the light received from the light scoop system. The following table summarized the DF of part one. Note that the resultant DF is significantly less than the DF found in existing condition. While this may seem contradictory to the point of the proposed system, it is actually quite logical because the insertion of a light scoop will effectively reduce the sky component (as the way the sky component is found depends on the angles from the locus to the upper and lower bound of the window area). Inserting an object at the window will affect the angles significantly.

Table E:

Locus	Sky Component (SC)				Externally Reflected Component (ERC) Total*Avg.reflectance(0.4)	Internally Reflected Component (IRC)	Daylight Factor (DF) DF = SC + ERC + IRC	Correction Factor	Final DF
	South	West	East	Total					
1	0.36	0.72	1.86	**2.94**	**1.18**	**0.47**	**4.59**	**0.33**	**1.51**
2	0.07	0.36	0.23	**0.66**	**0.26**	**0.47**	**1.39**	**0.33**	**0.46**
3	0.02	0.0	0.29	**0.31**	**0.12**	**0.47**	**0.90**	**0.33**	**0.30**
4	0.18	0.1	0.53	**0.81**	**0.32**	**0.47**	**1.60**	**0.33**	**0.53**

Table E summarizes the illuminance calculated from the above DF and the amount of illuminance from the light scoop. The total illuminance at each locus is also listed. The illuminance augmented by the light scoop is derived from the following equation:

$E_{\text{horizontal outside}}$ x p_{ceiling} x $p_{\text{anodized aluminum}}$ x portion of the sky exposed to light scoop

$E_{\text{horizontal outside}}$ is 7600, same as before, the reflectance coefficient of ceiling is 0.7, also same as before. The reflectance of the light scoop, which is made out of anodized aluminum, an extremely reflective material, is estimated to be 0.95. The portion of the sky that the scoop is exposed to estimated to be about 1/15. Using the above equation and these assumptions, the scoop augments the illuminance at each locus by about 337 lux. The final illuminance at each locus for the proposed system is thereby reaching a range of around 360 lux to 450 lux, as shown in Table F.

Table F:

Locus		E_h (lux)		$E_{p\text{-raw}}$ (lux)		$E_{p\text{-anidolic}}$ (lux)		$E_{p\text{-final}}$ (lux)
1		7600		**115.01688**		**337**		**452.01688**
2		7600		**34.96152**		**337**		**371.96152**
3		7600		**22.67232**		**337**		**359.67232**
4		7600		**40.22832**		**337**		**377.22832**

SUMMARY

Based on the above calculations, the Daylight Factors for each locus, as summarized in Table G, showed dramatic increase as a result of the light scoop system. An average increase overall was calculated to be at least 4.33, illustrating the success of the proposal.

Table G:

Existing DF		**Improved DF**		**amount Increase**
1.80		5.95		**4.15**
0.52		4.89		**4.37**
0.31		4.73		**4.42**
0.60		4.96		**4.36**

It is important to note at this point that the calculations and methods are not necessarily completely accurate. As previously mentioned, daylight factor is in itself a somewhat unreliable source as it does not take into account certain sunlight behaviors and conditions. This is most easily illustrated in the final increases which, while successful, are in fact more successful than the typical complete use of an anidolic system. The typical anidolic offers a 3.3% increase in daylight factor, significantly lower than the 4.3% increase we have achieved .

Despite this, the project can still be deemed a success. Looking at the qualitative and quantitative improvements, and the initial lighting conditions compared to those following the installation of the light scoop specifically, the increase in daylight, even if slightly inaccurate, is not to be denied. As the overall design concept also included electric lighting, it is also feasible to assume that the initial goals of 400-600 lux can still be reached regardless, and that this goal can be achieved while maintaining pleasant contrast and visual comfort, deflecting glare, and retaining human autonomy and operability. However, electric lighting aside, as this project was an exploration in improving daylight quality as first and foremost, the increase in daylight that the proposed system assumes is substantial, and justifies a successful study.

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