Relation between occupant perception of brightness and daylight distribution with key geometric characteristics in multi-family apartments of Malmö, Sweden

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Abstract. Focusing on subjective evaluations of daylight conditions, the present paper explores the relation between room geometric characteristics and perceived brightness and daylight distribution in residential spaces. The study was conducted in 35 apartments consisting of 105 different rooms in the city of Malmö, and selected with respect to typical Swedish architectural building typologies. Questionnaires were distributed by mail to participants, and apartments were surveyed to deduct key geometric characteristics. Results include a reliability analysis of the utilized questionnaire and a correlation study that showed the prevalence of both window size and number as key factors relating to perceived daylight conditions.

Keywords: daylighting; perception; residential; geometric characteristics

1. Introduction

Following the adoption of the European Daylight Standard EN-17037 [1] by the Swedish Standards Institute [2], policy makers in Sweden are considering updating the daylight requirements stated in the current building code BBR – BFS 2011:6 [3]. Implications of daylight regulations internationally have previously been investigated [4], and there seems to be consensus in founding guidelines on climate-based daylight evaluations [5]. Such evaluations imply the use of photometric benchmarks to ensure adequate daylighting, which in turn relates to occupant health and well-being [6]. Tregenza and Mardaljevic conclude in a seminal paper [7] that daylighting is not a single research topic, but rather a multi-disciplinary field consisting of several distinct strands, such as mathematical sky models, indoor daylight availability, glare analysis, window technology and user preferences. The latter involves, among other things, assessing when occupants perceive a room as sufficiently bright or evenly daylit, which are key daylight qualities in residential spaces where tasks are not strictly defined, compared to office spaces. The assessment may be made by comparing subjective assessments to photometric measurements or to geometric measurements. The present study focuses on the latter, with the aim to provide information regarding key geometric characteristics of multifamily residential spaces and their relation to perception of brightness and daylight distribution by inhabitants. The goal is to link occupant

[1] European Daylight Standard EN-17037
[2] Swedish Standards Institute
[3] BBR – BFS 2011:6
[4] Previous investigations
[5] Climate-based daylight evaluations
[6]Occupant health and well-being
[7]Seminal paper by Tregenza and Mardaljevic
perception of daylight conditions with simple design features of apartments, which could help develop simplified design rules.

2. Method
The study involved three distinct stages: 1) selecting, surveying and modelling the apartments with their actual geometric characteristics, 2) developing and distributing a questionnaire that pertains to perception of brightness and daylight distribution and 3) performing a statistical analysis on the retrieved data to derive correlations between geometric characteristics and perception of daylight conditions. The following sections describe each step in more detail.

2.1. Selected apartments and assessed geometric characteristics
The studied apartments are located in the central and metropolitan region of Malmö (Lat: 55,61°), and were selected to belong to six typical building typologies, identified in relevant Swedish planning research [8, 9]. Figure 1 shows the evaluated buildings, the amount of apartments included in the present study and the urban density of surroundings for each building type.

Surrounding objects (buildings and trees) were considered in a 200 m radius around each investigated building, and were modelled as LOD2 volumes. Their footprints were retrieved in vector format [10] and processed in ArcGIS ArcMap [11] in conjunction with recent Lidar data available from Swedish Surveying and Cadastral Agency [10] to retrieve 3D geometries. The geometries were further processed in the programming environment of Grasshopper [12] to cull surroundings within the 200 m radius. This
process has previously been described in detail in [13]. The evaluated apartment plans were modelled according to documentation drawings retrieved in raster or pdf format from Malmö City Planning Office [14], and apartment dimensions were validated with on-site measurements in at least three apartments per building. Following the Swedish regulation, rooms only included spaces where people stay more than occasionally: bedrooms (B), living rooms (L) and kitchens (K).

For each room, geometric characteristics included the window area (Awin) and its relation to the external wall area (WWR), to the floor area (WFR) and to the room walls area (WRoomWR). Façade characteristics included the number of fenestrated walls (NrWallsWin) and the area of the external wall (AextWall). To assess the effect of surroundings on each room, the Vertical Sky Component (VSC) was calculated based on the method defined by Littlefair [15], which involves a CIE Overcast Sky. The Radiance raytracer [16] via Honeybee [17] was used to compute the VSC, for a 0.1 m grid of points on the window surface, and an α-ad rendering setting of 16384 for a high spatial resolution in the raytracing of the sky dome.

2.2. Observer-based environmental assessment

The questionnaire items were based on seven-grade bipolar rating scales according to the method developed by Johansson et al. [18]. The questionnaire focused on two perceived daylight qualities: 1) brightness and 2) distribution. Figure 2 shows the segment of the questionnaire that referred to the living room (the same items were used for the kitchen and for the largest bedroom of the apartment). Four items referred to the perception of brightness and three to daylight distribution. The semantic differentials defined by these bipolar adjectives were used in this study (and have been developed) in the Swedish language, which makes them suitable in the context of Scandinavian culture. They are presented here in English to facilitate reading. The participants were asked to 1) be inside the specific room when filling the corresponding items, 2) answer during daytime, 3) switch off electric lighting and 4) pull all curtains/blinds fully open prior to answering.

![Figure 2](image-url)

**Figure 2:** The seven-grade bipolar scales used to assess perception of brightness and distribution. The same scales were used for the kitchen (K) and bedroom (B).

The questionnaire was distributed by normal mail to 945 addresses, on March 13, 2018, to ensure it would be filled during a period close to the spring equinox. The response rate was approximately 11% (108 questionnaires). Among the 108 returned questionnaires, 80 were complete and 75 of them were used in this study as they corresponded to apartments that included all three room types (N=225 rooms, for 75 respondents). The majority of questionnaires were filled during March.

2.2.1. Data processing. Principal component analysis (PCA) was conducted on the questionnaire items using orthogonal rotation (varimax) based on eigenvalues < 1, to derive two factors, one per daylight
quality. The degree of reliability for the correlation between the initial raw scores and the derived factors was evaluated using Cronbach’s Alpha. Associations between the derived factors and the geometric characteristics were then tested with Spearman’s rank correlation.

3. Results and discussion

3.1. Exploratory factor analysis and reliability analysis of questionnaire items

The results of the exploratory analysis on the items of the returned questionnaires (N=225) are shown in Table 1. The process was conducted for each room type, where the letters K, L, B correspond to Kitchen, Living room and Bedroom respectively. Factor loadings of items transformed to final factors used for correlating with geometric parameters are shown in bold, and the corresponding Cronbach’s alpha value of the reliability analysis is shown next to them. The PCA returned two factors per room type. The Brightness factor consistently included the following four items: dark – light, clear – drab, strong – weak, subdued – brilliant. The analysis showed a good internal reliability ($\alpha > 0.85$) for all four items, in all three room types. Therefore the average of these four items was used for correlations with the geometric characteristics. The Distribution factor consistently included two items: scattered – concentrated, unfocused – focused. The reliability of their factor was also high ($\alpha > 0.85$) for all items and rooms. Item uneven – even distributed was not included in the same factor for all room types and was therefore excluded from the study.

Table 1. Summary of statistical analysis (N=225). Factor loadings of items included in the final factors are shown in bold.

| Item                        | Rotated factor loadings (varimax) and Cronbach’s alpha |
|-----------------------------|--------------------------------------------------------|
|                             | Brightness K* loading alphaBrightness L* loading alpha |
|                             | Distribution K* loading alphaDistribution L* loading alpha |
|                             | Brightness B* loading alphaDistribution B* loading alpha |
| Dark — Light                | 0.836 0.902 0.073 | 0.857 0.929 -0.097 | 0.886 0.939 0.032 |
| Clear — Drab                | 0.718 0.848 0.276 | 0.779 0.922 -0.358 | 0.879 0.946 0.035 |
| Strong — Weak               | 0.815 0.905 0.043 | 0.884 0.952 -0.132 | 0.894 0.956 0.034 |
| Subdued — Brilliant         | 0.823 0.904 -0.222 | 0.907 0.932 -0.017 | 0.893 0.952 0.215 |
| Uneven — Even distributed   | -0.628 0.273 -0.416 | 0.555 -0.789 0.046 |
| Scattered — Concentrated    | -0.297 0.833 0.893 0.017 | 0.87 0.875 -0.184 | 0.902 0.895 |
| Unfocused — Focused         | 0.491 0.711 0.858 0.666 | 0.471 0.847 0.492 | 0.675 0.867 |

* K, L, B refer to Kitchen, Living room and Bedroom respectively

3.2. Associations between geometric parameters and observer-based environmental assessment

The correlation between perceived daylight conditions (factors Brightness and Distribution) and the geometric characteristics of rooms is shown in Tables 2 & 3. The rooms characterized for the present paper were 135 in total, and were divided into two samples, based on the existence of a balcony obstruction. Samples A (N = 105) and B (N = 30) include rooms without and with balcony respectively.

In sample A, Brightness correlates strongly with the window area (Awin, $r = 0.531, p < 0.001$) and with the window-to-wall ratio (WWR, $r = 0.481, p < 0.001$). However in sample B, it is more strongly correlated with the number of different walls that are fenestrated (NrWallsWin, $r = 0.431, p < 0.02$). This can be attributed to the fact that the spaces with an opening to a balcony are shaded by the balcony of the upper floor, but when they have a second window (e.g. on a different wall or away from the balcony), the shading of the first window is not perceived as negative anymore. An interesting outcome for both samples is that Brightness is associated less with the VSC than with the window size (Awin). This practically implies that even in denser urban areas (low VSC), a sufficiently fenestrated room may be perceived as adequately bright, perhaps due to the compensation offered by a generous view out. This was the case with building type “Large Courtyard”, where larger window sizes compensated for its dense surroundings (79 % of rooms were graded neutral or higher along the Brightness scale).
The Distribution factor was shown to correlate more strongly with the number of fenestrated walls in Sample A (NrWallsWin, \( r = 0.329, p < 0.005 \)). In addition, Distribution was found to correlate stronger with measures pertaining to window size than with the WFR, which is a value related to floor area. However, the small size of Sample B (\( N = 30 \)) may explain why no significant correlation was found between Distribution and all geometric characteristics, for the rooms with balconies.

**Table 2.** Spearman’s rank correlation between the Brightness and Distribution factors and the geometric characteristics of rooms without balcony (Sample A, \( N = 105 \)).

| \( N = 105 \) | Brightness | Distribution | VSC | Awin | WWR | WFR | WRoomWR | NrWallsWin | AextWall |
|--------------|-----------|--------------|-----|------|-----|-----|---------|------------|---------|
| Brightness   | 1         | 0.222        | 0.138| 0.531**| 0.481**| 0.341**| 0.473**  | 0.312**    | 0.340**  |
| Distribution | 1         | 0.271*       | 0.178| 0.232*| 0.092 | 0.274*| 0.329**  | -0.042     |         |
| VSC          | 1         | 0.339**      | 0.239*| 0.043 | 0.275*| 0.289*| 0.305**  | 0.535**    |         |
| Awin         | 1         | 0.834**      | 0.644**| 0.888**| 0.856**| 0.552**|         |           |         |
| WWR          | 1         | 0.794**      | 0.880**| 0.356**| 0.187 |     |         |           |         |
| WFR          | 1         | 0.805**      | 0.358**| 0.227 |     |     |         |           |         |
| WRoomWR      | 1         | 0.358**      | 0.428**|     |     |     |         |           |         |
| NrWallsWin   | 1         | 0.341**      |     |     |     |     |         |           |         |
| AextWall     | 1         |             |     |     |     |     |         |           |         |

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

**Table 3.** Spearman’s rank correlation between the Brightness and Distribution factors and the geometric characteristics of rooms with balcony (Sample B, \( N = 30 \)).

| \( N = 30 \) | Brightness | Distribution | VSC | Awin | WWR | WFR | WRoomWR | NrWallsWin | AextWall |
|--------------|-----------|--------------|-----|------|-----|-----|---------|------------|---------|
| Brightness   | 1         | -0.049       | 0.331| 0.402**| -0.285| -0.165| 0.091   | 0.431*    | 0.377*  |
| Distribution | 1         | -0.170       | -0.070| 0.148| 0.055| 0.212| -0.137  | -0.042    |         |
| VSC          | 1         | 0.662**      | -0.591| -0.235| -0.097| 0.877**| 0.596**  |           |         |
| Awin         | 1         | -0.381*      | -0.308| 0.340| 0.892**| 0.924**|         |           |         |
| WWR          | 1         | 0.662**      | 0.535**| -0.571**| -0.544**| -0.436*|         |           |         |
| WFR          | 1         | 0.543**      | -0.335| 0.196|     |     |         |           |         |
| WRoomWR      | 1         | 0.033        | 0.821**|     |     |     |         |           |         |
| NrWallsWin   | 1         | 0.821**      |     |     |     |     |         |           |         |
| AextWall     | 1         |             |     |     |     |     |         |           |         |

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

4. Conclusion

This article presents a study about perceived daylight conditions in multi-family apartments located in the city of Malmö. The study compares the subjective evaluations of occupants to the geometric characteristics of these dwellings. The main conclusions are stated below:

The observer-based assessment used here displays high internal reliability for the two dimensions studied (brightness and distribution). This consistency means that the assessment is trustworthy and usable for this purpose. A number of outcomes can be used for the development of simplified design rules. The results suggest that window size has the highest correlation with the perception of brightness for all rooms, including rooms in dense urban contexts. This might indicate the importance of view out as a key parameter. Another design-related aspect pertains to the balcony element. The results indicate that lower daylight levels resulting from the presence of a balcony may be compensated for by adding
an extra opening either on a different wall or in an unshaded portion of the fenestrated wall. Brightness perception was also found to correlate more strongly with the window size than with the Vertical Sky Component. Since the VSC is related to the surrounding urban density, this unexpected result implies that a simple view out may be sufficient in some cases, in absence of a view to the sky. It also reinforces the observation that a more generous view out somewhat compensates for lower daylight levels. This may have important implications in future developments of building regulations. Regarding perceived daylight distribution, it was found to have no correlation to the window-to-floor ratio. A stronger correlation was observed between distribution and the amount of fenestrated walls. This was an expected result since a higher amount of fenestrated walls should provide a better daylight distribution.

Overall, the results reveal a significant association between simple geometric characteristics and perceived daylight conditions. This could be considered prior to the development of future building regulations, as simple design rules can constitute complimentary material or alternatives to photometric requirements for specific cases. Illuminance information about these apartments could not be collected to a significant degree, due to time constraints and limitations in accessibility. Correlating perceived daylight conditions with photometric data is part of our future investigations.

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