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Lighting Layout Optimization for 3D Indoor Scenes

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Figure 1: *Left: Initial indoor scene with furniture installed (top view). Middle and right: Rendered scenes with lighting, for which the arrangement and intensity are automatically computed by our method. Lights are blue and yellow in the middle figure.*

Abstract

As the number of models for 3D indoor scenes are increasing rapidly, methods for generating the lighting layout have also become increasingly important. This paper presents a novel method that creates optimal placements and intensities of a set of lights in indoor scenes. Our method is characterized by designing the objective functions for the optimization based on the lighting guidelines used in the interior design field. Specifically, to apply major elements of the lighting guideline, we identify three criteria, namely the structure, function, and aesthetics, that are suitable for the virtual space and quantify them through a set of objective terms: pairwise relation, hierarchy, circulation, illuminance, and collision. Given an indoor scene with properly arranged furniture as input, our method combines the procedural and optimization-based approaches to generate lighting layouts appropriate to the geometric and functional characteristics of the input scene. The effectiveness of our method is demonstrated with an ablation study of cost terms for the optimization and a user study for perceptual evaluation.

CCS Concepts

• ***Computing methodologies*** → ***Graphics systems and interfaces;***

1. Introduction

Lighting plays an important role in the 3D scene: it provides necessary light for human activity and determines the overall mood and atmosphere of the scene. Lighting layout design is thus an important yet complex task. Even for an empty indoor space, the lighting arrangement should consider the type and size of the space as well as the type of lighting. Its complexity steeply increases with the existence of furniture. The complex geometries and reflectance properties of furniture make it difficult to analyze the effect of lighting on a particular surface when there are multiple light sources. In addition, each item of furniture requires different illumination intensity to accommodate particular human activities regarding the furniture. Therefore, the lighting must satisfy various conditions even in one small room. Moreover, if the arrangement of the furniture changes slightly, the lighting must also change accordingly.

Partly due to its complexity, modeling the lighting for a virtual indoor scene currently remains mostly the arena of the artist. Artists go through the iterative process of adjusting position, direction, and other parameters of lighting and evaluating the quality of the rendered scene. Thus, it takes an excessive amount time and effort to create appropriate lighting for many virtual scenes.

With the increasing demand for virtual indoor spaces, a number of studies have been conducted to automatically generate 3D indoor scenes [SYZ*17]. In contrast, research on generating lighting has received relatively less attention. Existing studies on lighting generation either ignored the characteristics of lighting as light sources considering them only as furniture [MSL*11], or ignored its relationship with other furniture considering only the functional aspect as the light source [GP16]. However, an appropriate lighting layout maintains a proper spatial relationship with other furniture and provides necessary illumination to the scene while satisfying the many constraints that depend on the characteristics of the 3D indoor scene and the furniture placed inside the scene.

In this paper, we present an automatic lighting layout generation system that creates optimized placements and illumination intensities of a set of lights in 3D indoor scenes. The main idea of this research is to apply the real-world design methodology to virtual spaces. Instead of manually placing lighting fixtures and judging the rendered scene by eye, applying the real-world principles on lighting design directly to the 3D scene will reduce the difficult and troublesome manual modification process. The principles of lighting layout can be found in the interior lighting design guidelines (e.g., [Ill11]).

Given a model of a 3D indoor scene with furniture as the input, our lighting generation system creates a set of lights and determines their placements and illumination intensities. To this end, we take a combined procedural and optimization-based approach to efficiently reflect various characteristics of lighting with respect to its spatial relationship with the space and furniture as well as its functional aspect as illuminator. Specifically, the ambient illumination that illuminates the entire space is first determined by a set of ceiling lights, which are arranged procedurally. Next, the placements and illumination intensities of local lights (e.g., floorstand) are determined with a sampling-based optimization algorithm. For this, we define a set of cost functions that evaluate the quality of a given arrangement with respect to the structure, function, and aesthetics, which are the major elements to be applied to virtual scenes among the elements suggested by interior lighting guidelines.

To validate the effectiveness of our method, we performed a user study that perceptually compared the automatically generated lighting using our system with that manually created by users. The results showed that the lighting layouts generated by our method were better or similar to the ones made by the general user on average in terms of structural, functional, and aesthetic evaluation criteria.

The major contributions of this study are as follows:

- First, we formulate and quantify important elements in the interior lighting guidelines used in the real-world interior architecture and apply them to the the virtual 3D indoor scene. To generate appropriate lighting layouts, we consider both aspects of luminaires as furniture and illuminator.
- Second, we develop an interactive system that allows novice users to easily create lighting layouts.

2. Related Work

Luminaires have the characteristics of both furniture and light sources, and thus lighting layout must take both aspects into account. In this section, we first review existing studies on analyzing and generating furniture layout as they deal with object arrangement in indoor scenes, a closely related subject to our problem. Then, we discuss previous research on lighting design. Existing software applications that can be used for lighting design are discusses next.

2.1. Furniture Layout

Furniture layout has been widely studied in mostly two directions: one is to generate indoor scenes and the other to analyze them. Xu et al. [XMZ*14] and Huang et al. [HFH16] proposed methods to analyze indoor scenes and measure the similarity between the scenes. Xu et al. [XMZ*14] introduced focal points that were defined as representative substructures in a scene and calculated the similarity between scenes using the focal points. Huang et al. [HFH16] represented each 3D indoor scene as a structure graph associated with a relationship set and established a furniture-object-based matching between scene pairs via graph matching. Kang and Lee [KL17] reconstructed furniture layouts from captured human motions interacting with furniture.

Several researchers have developed furniture arrangement methods that automatically create layouts under some constraints or rules [GS09, XSF02, MSL*11, YYT*11]. Germer and Schwarz [GS09] introduced an agent-based procedural approach and Xu et al. [XSF02] developed a constraint-based system that used a combination of automatically generated placement constraints, simplified physics, and a semantic database to guide the automatic placement of objects. Merrell et al. [MSL*11] presented an interactive furniture layout system that assists users by suggesting furniture arrangements obtained by optimizing cost functions based on interior design guidelines. Similarly, Yu et al. [YYT*11] suggested a method that encodes spatial and hierarchical relationships into priors associated with ergonomic factors, which are then assembled into a cost function. More recently, Kan and Kaufmann [KK] developed a method that uses both an optimization-based approach for global aesthetic rules and a procedural approach for local arrangement of small objects.

Similar to many studies mentioned above, we take an optimization-based approach that defines appropriate cost functions to find a desired result. The novel aspect of our research is that we identify cost functions that evaluate the quality of a lighting arrangement by simultaneously considering both aspects of lighting as furniture and illuminator, which naturally requires dealing with significantly more characteristics of illuminance conditions than the problem of furniture arrangement.

2.2. Lighting Design

Most studies on lighting design take an inverse approach that finds the attributes of light sources to realize desired brightness, color and shadow of objects or environments set by a user. Refer to [PP03] for the basic principles and the survey on the previous work for the inverse lighting problem, and to [GP18] for the detailed introduction on more recent studies.

To solve the inverse lighting problem, many researchers proposed techniques that find the light setting to closely match the desired target image painted by the user [SDS*93, SC07, GP16, OMSI07, PBMF07, LHH*13]. Schwarz and Wonka [SW14] introduced a procedural method for modeling exterior lighting. Following these previous approaches, we also take an optimization-based framework, specifically the simulated annealing technique that has been widely used in computer graphics, to determine lighting layout. Our work is contrasted with the previous work in that, aiming to automatically obtain appropriate lighting for a given indoor

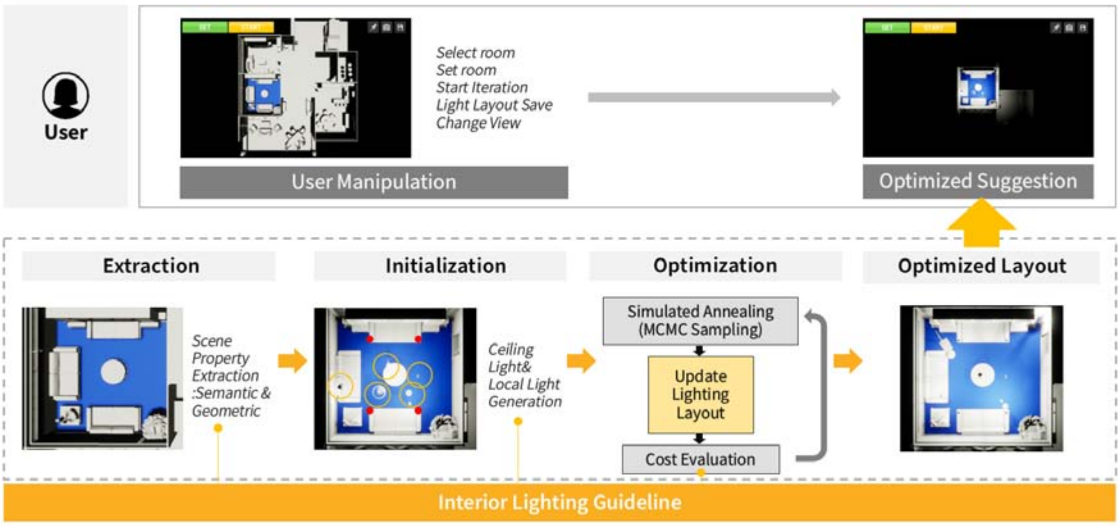


Figure 2: *System overview.*

scene, we adopt and quantify the industry standards for setting the structural, functional, and aesthetic goals for the lighting layout.

Sorger et al. [SOL*16] presented an interactive system that visualizes the effect of lighting to help users meet the desired conditions under industry standards. Our approach also uses lighting simulation based on industry standards, but additionally we redefine the standard to be applied to virtual indoor scenes and generate the optimal lighting layout. Lighting design that simultaneously considers the relationship between lighting and furniture in indoor scenes has been more or less overlooked. Yamakawa et al. [YDY16] propose a method to compute furniture layout for a given lighting environment, which may be useful for planning furniture layout in a real space where lighting placement is rather fixed. This is an inverse approach to ours, which computes lighting layout for a given furniture arrangement. Recently, Gkaravelis and Papaioannou [GP18] developed an optimization method to determine the lighting arrangement to highlight the geometric details of complex objects. The method is most suitable for a single object with complex geometry such as a sculpture while our work is developed for the indoor lighting layout. Nguyen et al. [NRM*12] solve a different yet related problem of transferring material style from a guided source, such as an image or video, to a target 3D scene.

2.3. Software Applications

Commercial interior design software is often used to assist users by visualizing furniture and lighting layouts and providing photorealistically rendered images. Applications that support lighting layout design can be briefly divided into interior design software and lighting design software. Interior design software, such as Sweet Home 3D [eTe] and Planner 5D [UAB], provides convenient tools to place lighting just like any other furniture. Lighting design software, such as Relux [Rel], AGi32 [Lig], and Dialux [DIA], normally uses illumination simulation for designing real architecture plans. None of the applications provide tools to automatically generate lighting in indoor scenes as our method does.

3. Lighting Layout Optimization

Figure 2 shows an overview of the proposed system. The top row shows the functions provided to the user, by which the user chooses a room in the whole plan to place lighting. Given the selected room, our system generates an optimized lighting layout. The bottom row shows the lighting generation process. First, the target room is analyzed to extract the geometric information, such as the size, position, and direction of the room, and the furniture as well as the semantic information, such as the room and furniture types. Then, lights are initially arranged, followed by iterative, sampling-based optimization to find the optimal placement and illumination intensities of the lights.

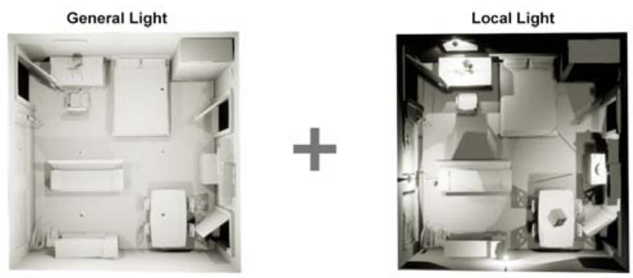


Figure 3: *Total illumination of a room is made by the composition of the general lights (ceiling lights, left) and the local lights (right).*

In this study, the lighting in the indoor space is divided into the general light that illuminates the whole space and local light that illuminates specific furniture and parts as shown in Fig. 3. Ceiling lights take the role of the general lighting, and other lights are local. Since the ceiling lights are normally arranged in a regular

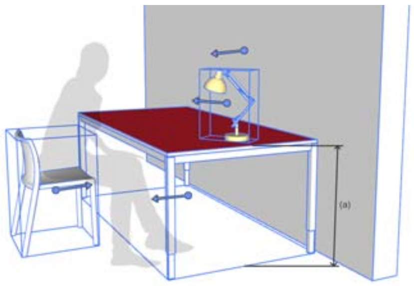


Figure 4: *Every object has a bounding box (blue line). The walls, furniture and luminaire models have a frontal direction. The top part of the desk (red) is the task plane. A table stand light is paired with the desk and it is automatically located at the desk height (a) initially.*

grid, their placements are determined procedurally according to the room type and shape. In contrast, the local lighting layout, which must be placed by considering the complex relationship between furniture and space, is solved through optimization.

3.1. Interior Lighting Guidelines

Lighting provides illumination for human activities and it also has a great influence on the visual and psychological aspects of space. Various international standards for lighting design provide a number of guidelines with respect to such functional and perceptual characteristics. Among these guidelines, some apply only to physical lighting design, such as electrical regulations, and others apply to virtual lighting design as well. In this study, referring to the guidelines suggested by the International Illumination Engineering Society of North America (IESNA) [Ill11], we identify important elements for virtual lighting design as follows:

- **Structure.** The structural conditions consider the structural characteristics of space, e.g., geometrical attributes such as area and depth.
- **Function.** The functional conditions provide appropriate illumination according to furniture types in order to support human activities.
- **Aesthetics.** Lastly, the aesthetic conditions emphasize that the placement of the lighting should support the hierarchy of space and that the lighting should be in visual harmony with other lighting and furniture.

In order to reflect these conditions in the lighting layout, we develop a set of cost functions. Before detailing these cost functions in Sec. 3.4, we first describe the furniture and luminaire models used in our study next.

3.2. Furniture and Luminaire Models

We extract the necessary information from and indoor space and perform procedural and optimization-based lighting placement using that information. A scene has complex information with many variables. We assume the structure, furniture, and lighting of the scene as follows to efficiently analyze and represent the scene. All

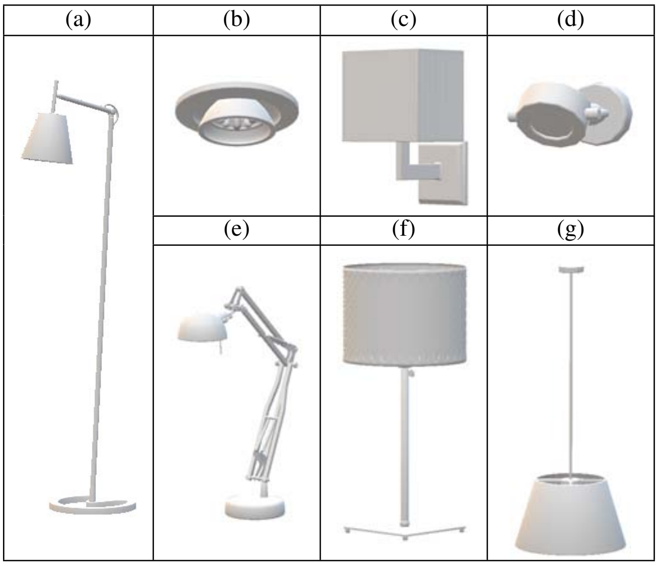


Table 1: *Example models of each lighting type. (a) Floor stand light placed on the floor. (b) Ceiling light recessed in the ceiling. (c) Bracket to the side of a wall with a point light source. (d) Bracket with a spot light source. (e) Table stand light on the desk. (f) Night stand light placed on a night stand beside the bed. (g) Pendant light mounted to the ceiling.*

objects have associated bounding boxes that represent the position and size of the objects, and frontal directions as explained next.

3.2.1. Structure and Furniture Models

In an indoor scene, the structure is a set of models defining the shape of a room, such as ceilings, walls, and floors. The wall has normal direction information that points inside the space.

All furniture models have directions, which are estimated from their position and direction relative to the wall. The furniture that interacts with people is assigned the task plane, which is the surface on which the interaction occurs. This task plane is set considering the direction of the furniture and the height of the top surface. Figure 4 shows the directions of objects and the task plane of a desk.

3.2.2. Luminaire Models

All luminaire models are divided into seven categories as shown in Table 1: Bracket (point light and spot light), floor stand light, table stand light, night stand light, pendant light, and ceiling light. Each type has different characteristics regarding the application, appearance, and placement. Each of the luminaire models has light source, which is the spotlight for one of the bracket types used to emphasize the artwork and the point light for all others. The direction of a light fixture is defined to be a horizontal vector from the base to the light source or an arbitrary direction for a symmetric model.

The attributes of the lights that are considered in the arrangement are the type, position, direction, and light intensity. Given the user-selected room, our system automatically generates the luminaires

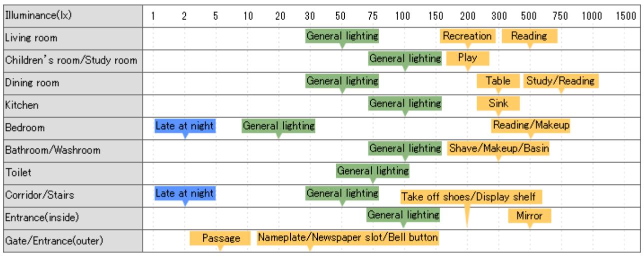


Figure 5: *Recommended illuminance range per room type and activity [Pan].*

associated with the existing furniture according to the pairwise relation as shown in Table 2. The position of a light is constrained to the contacting surface, such as the wall, ceiling or floor, and thus the light has 2 DoFs in position and 1 DoF in orientation.

3.3. General Light Layout

General light controls the overall uniform illumination within the space. Each space has different recommended illuminance depending on the activity that takes place in the space as shown in Fig. 5. For example, the recommended illuminance of the kitchen where cooking activity requires concentration is 75-150 lx, while that of the bedroom, which is mainly for resting, is 10-30 lx.

Therefore, the number of necessary ceiling lights depends on the type, area, and height of a room as well as the illumination intensity of a light bulb. In this study, when a user selects a room to arrange lighting, the system finds the necessary illuminance according to the room type from a table (Fig. 5), and automatically arranges ceiling lights corresponding to the structure of the room.

Placement Ceiling lights require regular arrangement of a number of identical lights in order to provide uniform overall illumination across the room. The number and spacing of the illumination are set according to the size and type of space. The number of ceiling lights N_{ceil} required throughout the space follows the formula redefined based on the lighting guidelines.

$$N_{ceil} = \frac{\text{Recommended Illuminance (lx)}}{\text{Luminous Flux (lm)}} \times \text{Area} \tag{1}$$

To arrange the ceiling lights at appropriate positions, they are placed in an A-by-B grid where the ratio of A and B is set to the aspect ratio of the room and $A \times B \approx N$.The illumination intensity of the ceiling light is set to the intensity of the general ceiling light in a real-world environment. Fig. 1 (middle) shows an example of the arranged ceiling lights in yellow.

Removal The ceiling light arrangement may be modified by the local lights during the optimization process. A pendant light, one of local light types, is also attached to the ceiling, and if it is too close to a ceiling light, the room will become too bright at a certain spot and strong shadows will be generated around the pendant light. In order to prevent this, a ceiling light $l_{c,0}$ that is closest to a pendant light l_p is removed if $d(l_p, l_{c,0}) < \alpha \cdot d(l_p, l_{c,1})$ where $d(\cdot,\cdot)$ denotes the closest distance between two object geometries and $l_{c,1}$ is the next closest ceiling light. In our study, α is set to 0.5. During the optimization process, a removed ceiling light is restored if the pendent light is moved farther from the ceiling light.

Figure 6: *Pairwise relation example: the wall and the bracket (left), and the desk and the table stand light (right).*

Table 2: *Pairwise relationship.*

Furniture/Lighting	Distance(cm)		Overlap		Position
	min	max	min	max	
(Sofa, Floor stand)	20	80	0	0.3	side
(Desk, Table stand)	0	0	0.15	0.8	on
(Table, Pendent)	0	30	1	1	on
(Wall, Bracket)	0	0	0	0	side
(Night stand, Table stand)	0	0	0	0	on
(Artwork, Spotlight)	0	0	0	0	on

3.4. Local Light Layout

Local light is used to illuminate a partial region in a space. As person interacts with furniture, the local light provides necessary illuminance to a task plane where the interaction takes place. In order to arrange lighting in a room, many factors must be considered, such as conforming to the semantic and geometric characteristics of space and satisfying structural, functional, and aesthetic requirements set out in the lighting guideline. To this end, the local lighting layout is generated by optimizing the cost function that quantitatively evaluates these factors. We define this cost function with five terms: *pairwise relation, hierarchy, circulation, illuminance,* and *collision*. We now describe each cost term in detail.

We represent the overall layout including lighting and furniture in a room as $\Theta = (R, F, L)$, where R is the bounding box of the room which the user selects, F is the set of furniture items contained in the room, and L denotes the set of lights in the room.

3.4.1. Pairwise relation

Certain types of lighting and furniture have a close relationship. For example, as shown in Fig. 6, the bracket is always attached to a wall, and the table stand and the desk appear together. We represent the relationship between a light and related furniture or other objects in terms of distance, overlap, and position as shown in Table 2. They define the allowed distance and the degree of overlap between the two entities, and the position of the light with respect to the furniture. Given an indoor scene, our system creates a local light for each furniture item that has a pairwise relationship with a light. The cost term for each attribute is detailed next.

3.4.1.1. Distance The distance between furniture and lighting is defined as the minimum distance between two object geometries.

Figure 7: *Overlap example.*

The distance cost function $C_{pd}(\Theta)$ of the pairwise relationship between furniture and lighting is

$$C_{pd}(\Theta) = \sum_{f\in F}\sum_{l\in L} \mathbb{1}_{pair}(f,l)\cdot \Upsilon(d(f,l), \underline{d}_{f,l}, \bar{d}_{f,l}), \quad (2)$$

where $(\underline{d}_{f,l}, \bar{d}_{f,l})$ is the minimum and maximum values of the recommended ranges of distance defined in Table2, and $\mathbb{1}_{pair}(f,l)$ is an indicator function that outputs 1 if there is a pairwise relationship between furniture f and lighting l, and 0 otherwise. The cost function Υ is defined as

$$\Upsilon(d,m,M) = \begin{cases} 1-\frac{d}{m}, & \text{if d < m} \\ 0, & \text{if } m \le d \le M \\ 1-\frac{M}{d}, & \text{if d > M.} \end{cases} \quad (3)$$

Thus, Υ is 0 when d is within the recommended range $[m,M]$ and increases as it deviates from the range. We modified a function suggested by Merrell et al. [MSL*11] for Υ.

3.4.1.2. Overlap The overlap defines how much the object and light should overlap from the top view. In the case of the desk and table stand, the stand is always located in the corner of the desk. To quantify the extent of overlap of light $l(\in L)$ and furniture $f(\in F)$, we use the bounding box of objects as follows:

$$o(f,l) = 1 - \frac{d_{cen}(f,l)}{hlen(f)+hlen(l)}, \quad (4)$$

where $d_{cen}(f,l)$ denotes the distance between center points of the bounding boxes of f and l in the top view, and $hlen(x)$ is the half-length of the bounding box of x. Therefore, the overlap value is 0 when they are attached without a gap, and 1 when the center points coincide as shown in Fig. 7. The recommended overlap value of desk and table stand is between 0.15 and 0.8 as a table stand is usually placed near the side of the desk.

The overlap cost function of furniture and lighting $C_{po}(\Theta)$ is defined as follows:

$$C_{po}(\Theta) = \sum_{f\in F}\sum_{l\in L} \mathbb{1}_{pair}(f,l)\cdot \Upsilon(o(f,l), \underline{o}_{f,l}, \bar{o}_{f,l}), \quad (5)$$

where $(\underline{o}_{f,l}, \bar{o}_{f,l})$ denotes the recommended range of overlap defined in Table 2.

3.4.1.3. Position and angle The allowed position of the light is defined by the position field in Table 2. If it is *on*, a light is placed on or over the task plane of the furniture. Therefore, the base height of the light is fixed at the task plane of the furniture, the ceiling, or above a certain distance of an object, and the light can only move in the horizontal plane. If it is *side*, a light is placed to the side of its pairing object. An example of the initial height of each lighting is described in Sec. 3.2.1

Unlike other lighting types that have a degree of freedom of direction, the bracket must be parallel to the normal direction of the wall. An additional cost term $C_{pa}(\Theta) = \sum_{l\in L_{bracket}} ||\vec{w} - \vec{l}||^2$, where $\vec{w}$ and $\vec{l}$ denote the directions of the wall and light, enforces this constraint.

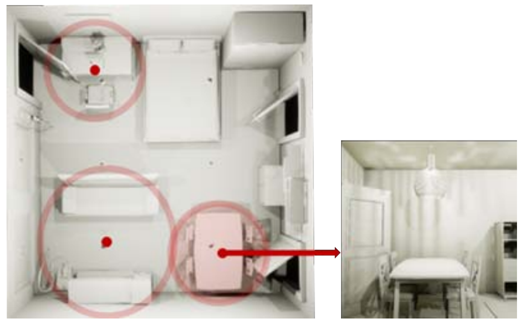


Figure 8: *The pendant lighting, which has a decorative characteristic, is placed in the central furniture group to form the hierarchy.*

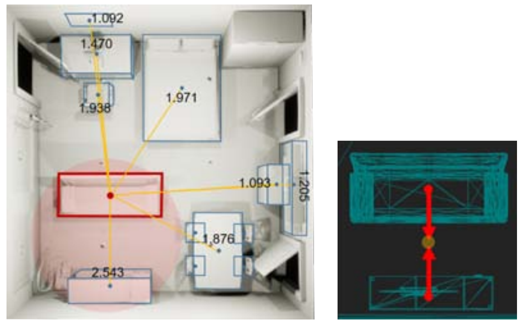


Figure 9: *Left: The connection strength between the sofa in the middle and the surrounding furniture. Right: Example of the focal point in the furniture group formed based on the connection strength.*

3.4.2. Hierarchy

The hierarchy of space, one of the most important principles in architecture, represents a horizontal hierarchy that emphasizes an important area, which is recognized by its shape as well as its functional, formal and symbolic roles. To reflect the hierarchy, various methods are used in the real world, such as changing shape, size, and color of objects, or by strategically arranging the objects. In our study, we use the lighting arrangement to emphasize the hierarchy.

To this end, we first analyze the hierarchy of horizontal space. Specifically, we first find an area or a group of furniture items that is important in the room from the viewpoint of the arrangement of furniture. Then, we identify central groups consisting of important furniture among the existing furniture items and determine their center point as shown in Fig. 8. The spatial hierarchy is emphasized by arranging lighting with decorative features around the center point.

We use the *connection strength* suggested by Xu et al. [XMZ*14] to identify which groups of furniture play an important role in the overall room.

$$\text{Connection Strength}(f,g) = \frac{diag(f)+diag(g)}{d(f,g)} \quad (f,g \in F) \quad (6)$$

The connection strength is the sum of the diagonal lengths of the furniture's bounding boxes divided by the distance between two furniture objects. If a furniture object has a large bounding box, it can be connected to relatively far piece of furniture, and vice versa.

We measure the connection strengths between all furniture pairs. Two furniture objects form a group if their connection strength is high enough and their orientations face each other. The group is built by including other furniture that has overlapping bounding boxes with those of the two furniture objects. The area center point of the formed group is set as an important point, called the *focal point* in this study.

The cost terms related to the hierarchy are as follows. First, we define the distance cost function of the hierarchy as

$$C_{fd}(\Theta) = \sum_{l \in L_{pend}} \frac{d(l,p_{near})}{d(l,p_{far})}, \quad (7)$$

where p_{near} and p_{far} denote the closest focal point and the farthest focal point from the location of the lighting l. This term encourages the pendant light to be close to the near focal point. The division by $d(l,p_{far})$ is a normalization term, and it is removed if there is only one focal point in a scene. The second cost function of the hierarchy is about the angle. To emphasize the focal point, we encourage the direction of the lighting to face towards the focal point.

$$C_{fa}(\Theta) = \sum_{l \in L_{pend}} \phi(l,p_{near}), \quad (8)$$

where $\phi(l,p_{near})$ denotes the angle between the facing direction of the light l and the vector from the l to p_{near}.

3.4.3. Circulation

In order to maintain the function of the room, it is necessary to consider the person's moving paths in the existing layout. Circulation is a line indicating the trace in which a person moves. It is ideal that newly placed lighting would not affect the circulation made by existing objects and furniture. To measure this, we use a Voronoi graph, which can be used to find the paths among objects and the wall. The Voronoi graph is often used for robot motion planning to evaluate the circulation of indoor space. The circulation cost term is defined as

$$C_{ci}(\Theta) = |N(F) - N(F \cup L)|, \quad (9)$$

where $N(F)$ and $N(F \cup L)$ are the number of components connected to movable paths, computed from the Voronoi graph, when there is only furniture and when lighting is added, respectively. That is, we endeavor to maintain the number of connected components in the initial layout even if lighting fixtures are placed.

3.4.4. Illuminance

Various activities that occur during the human-furniture interaction requires varying illumination intensities depending on the characteristic of the activity, including the extent of necessary visual concentration and the type of space. Therefore, even in a small space, the recommended illuminance varies depending on location.

Figure 10: *Sample points scattered at regular intervals to measure illuminance on the task plane.*

Our goal was to obtain the optimal lighting that provides the recommended illumination throughout the space. This is a challenging problem because of the complex optical interaction between lights and surfaces. A light source affects the illuminance of the surfaces through direct lighting and an infinite number of reflections. Illuminance intensity at a surface point is the composition of a number of light sources in a space.

To simplify this problem, we used a method to calculate direct light and indirect light from sample points distributed on a task plane of furniture as shown in Fig. 10, and took only diffuse reflections from the surface into account while ignoring specular reflections. In our experiment, sample points S are distributed by an interval of about 30 cm. Each sample point has a recommended illuminance $L_{rec}(\cdot)$ defined per furniture type. Because it is difficult to precisely reach the recommended illuminance, we set a recommended illuminance range L_{rnd}:

$$L_{rng}(s) = [L_{rec}(f)(1-\beta), L_{rec}(f)(1+\beta)] \quad (s \in S), \quad (10)$$

where the tolerance coefficient β is set to 0.2 in our work.

The illuminance function $L(\cdot)$ at each sample point s is defined as the sum of the direct light $L_{dir}(\cdot)$ and the indirect light $L_{ind}(\cdot)$. Direct and indirect light are measured from all the light sources in the room.

$$L(s) = L_{dir}(s) + L_{ind}(s) \quad (s \in S) \quad (11)$$

The direct light is efficiently calculated but indirect light computation may take an excessive amount of computation if done accurately, which makes the optimization prohibitively slow. Therefore, we simplify the indirect light computation: we conduct the Monte Carlo integration of the rays cast from the sample points, with the reflection bounded only once on a surface within a certain distance. We used the Phong illumination model for the diffuse reflection. Note that, although we experimented with only white objects as they can show lighting effect clearly, our system can consider different surface albedos represented with the Phong diffuse reflection parameter. For example, low surface albedo leads to the increase of the light intensity.

The cost function for the total illumination is defined as follows.

$$C_{il}(\Theta) = \sum_{s \in S} \Upsilon(L(s), L_{rng}(s)) \quad (12)$$

This cost term is the only term that is involved in determining the

Figure 11: *Diverse indoor scenes including lighting layout generated by our system. The four scenes are seen as a perspective view on the left and a top view on the right. In the top view image, local light is marked in blue and general light (ceiling light) is marked in yellow. The left column shows the living room and the studio, and the right column shows the two different private rooms.*

light intensity. At the same time, this term has a significant influence on the light arrangement as well. For example, it can prevent a light from being positioned to cast a strong shadow on a task plane.

3.4.5. Collision

Finally, we add the collision term C_{col} to the cost function so that the lights do not collide with furniture, wall, or other lights. The collision term is defined as the penetration depth of a light into other objects.

3.5. Optimal Layout Generation

A candidate lighting layout L is evaluated with the total cost function:

$$C_{R,F}(L) = \sum_i w_i C_i(\Theta), \tag{13}$$

where $i \in \{pd, pa, po, fd, fa, ci, il, col\}$ and w_i is the weight of each term.

The simulated annealing method is used to quickly approach the optimal solution. For this, a new sample layout is created by sequentially applying below operations to all local the lights.

- Move: Translate lighting by real numbers drawn from a distribution $N(0,\sigma^2)$.
- Rotate: Vertically rotate lighting by a real number drawn from a distribution $N(0,\sigma_\theta^2)$.
- Swap: Swap positions of two randomly selected lights with a probability p_s.
- Strength: Change the intensity by a real number drawn from a distribution $N(0,\sigma_s^2)$.

The layout evaluated by the cost function is sampled through a Markov Chain Monte Carlo sampler. Specifically, the probability $p(L)$ of L is defined as $p(L) = \exp(-\gamma \cdot C_{R,F}(L))$, where γ denotes the temperature constant. Then the Metropolis-Hastings algorithm was used to stochastically accept the new lighting arrangement L^* from the current lighting arrangement L, i.e., the acceptance probability is determined by $\min(1, \frac{p(L*)p(L|L*)}{p(L)p(L*|L)})$.

We stop the iteration when the cost no longer decreases by a certain threshold below the average cost value of the previous 20 iterations. The parameters for the optimization were determined manually from a number of trials. The weights were set to 1.0 (w_{ci}, w_{fa}), 1.2 (w_{pa}, w_{po}, w_{fd}), 2.0 (w_{col}), and 3.0 (w_{il}, w_{pd}), respectively. We set 7.0 for σ and σ_s, and 5.0 for σ_θ. The optimization typically takes about 6 to 7 minutes with a computer equipped with Intel Core i7 CPU, 8GB RAM, and a GeForce GTX 1060 graphics card.

4. Result

The proposed system created the lighting layout for the living room, private room, studio and office as shown in Fig. 11. We implemented the system using Unreal Engine 4 and used the SunCG dataset [SYZ*17] for the entire indoor scenes and lighting data.

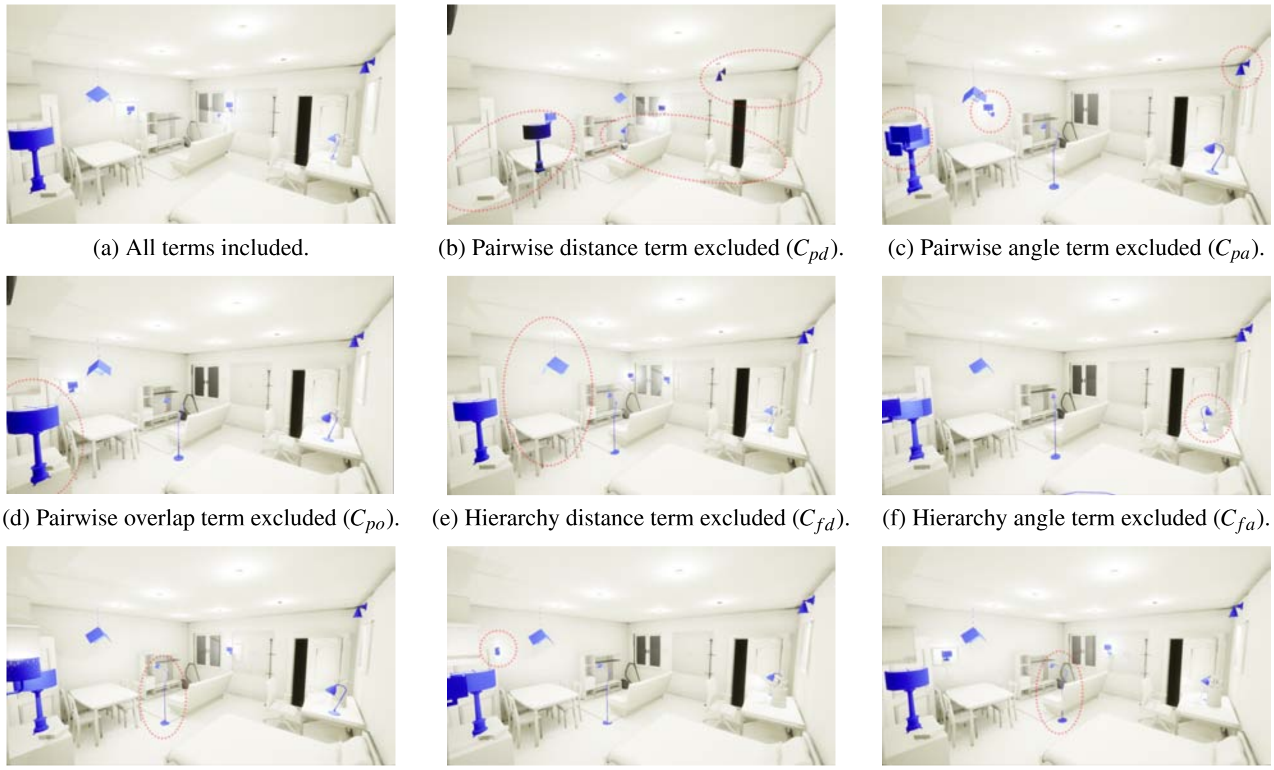
4.1. Cost Terms

Figure 12 shows the experiments where lighting layouts are generated while each term is excluded from the cost function. The experiments show that each cost term plays an indispensable role to create appropriate lighting.

4.2. Perceptual Evaluation

We performed a user study to evaluate the lighting layout automatically generated by our system. The goal was to verify whether the lighting layout created by the system was significantly different from those produced by ordinary people without professional architectural training. Our null hypothesis $H0$ was that there is no significant difference in terms of functional, aesthetic, and structural aspects between the two, and the alternative hypothesis $H1$ was that there is significant difference between them.

Four participants who had not received professional architectural education were recruited. Each participant was asked to manually



(a) All terms included. (b) Pairwise distance term excluded (C_{pd}). (c) Pairwise angle term excluded (C_{pa}).

(d) Pairwise overlap term excluded (C_{po}). (e) Hierarchy distance term excluded (C_{fd}). (f) Hierarchy angle term excluded (C_{fa}).

(g) Circulation term excluded (C_{ci}). (h) Illuminance term excluded (C_{il}). (i) Collision term excluded (C_{col}).

Figure 12: *The effect of each term of the cost function: (a) The proposed lighting arrangement with all terms included. (b) The lights are located far from their pairing objects. (c) The directions of the wall and the bracket do not match. (d) The light is placed unnaturally on the paring object. (e) The pendant light is not located in the center of the dining table. (f) The table stand light is facing the wall. (g) The floor stand light is blocking a path. (h) The bracket illuminates areas needlessly. (i) The floor stand light penetrates into the sofa.*

place lighting fixtures in each of the five indoor scenes. Our system also created the same number of layouts in the same five indoor scenes. Among several 3D lighting fixture models for each light type, our system randomly selected a light fixture model for a chosen light type. In the user study, the participants selected their preferred light fixture models. A total of 40 layouts were randomly presented to 38 participants, and we asked them to evaluate questions based on the indoor lighting guidelines. Figure 13 shows some of the layouts used for the evaluation.

We devised a questionnaire to evaluate the lighting guidelines described in Sec.3.1. First, the evaluation of the functional condition was about whether the whole room and the task plane of the furniture had adequate illuminance and whether it gave visual fatigue. Second, under aesthetic conditions, we asked whether each of the lighting fixtures has a harmonious array and follows the hierarchy of space. Finally, we evaluated whether the lighting arrangement is suitable for the geometrical environment of the room under the structural condition. Specific questions are listed below.

- Function
  - Q1 (BRI): This space looks bright enough.
  - Q2 (COM): The lighting in this space looks visually comfortable.
  - Q3 (INT): Each lighting has proper placement and brightness to interact with the furniture.
- Aesthetics
  - Q4 (HAR): The position and arrangement of each illumination is harmonious.
  - Q5 (HIE): The placed lighting allows to see which part is important in this space.
- Structure
  - Q6 (STR): The brightness and number of the overall lighting is suitable for the size (width and height) of the space.

Table 3 shows the results of the paired T-test by dividing each question evaluated by 38 participants on a 10-point scale into the layout of the participant and the layout of the system. The aggregate result (Table 3(bottom) and Fig. 14) shows that our system marked higher average scores than the manual placements over all the questions, among which Q1 (BRI) and Q6 (HIE) showed statistical significance ($p < 0.05$) while others did not. In case of the studio, private rooms #1 and #2, the layouts of the system showed higher average scores in most questions. One can see that the lighting generated by our system creates more uniform illumination throughout the space. The average scores of the participants' lay-

Table 3: *Lighting layout evaluation analysis.*

		BRI	COM	INT	HAR	HIE	STR
Living	Participant	6.710	6.697	6.868	6.763	6.907	6.815
	System	6.565	6.644	6.565	6.539	6.631	6.460
	P-value	0.474	0.825	0.239	0.425	0.244	0.163
Private1	Participant	6.013	6.447	6.157	6.157	6.197	6.131
	System	6.828	6.815	7.223	6.776	6.986	7.013
	P-value	0.039	0.310	0.003	0.142	0.035	0.028
Private2	Participant	6.684	6.855	6.644	6.605	6.763	6.565
	System	7.736	7.618	7.197	7.421	7.513	7.460
	P-value	0.001	0.015	0.086	0.142	0.001	0.004
Studio	Participant	6.039	6.697	6.513	6.605	6.578	6.486
	System	7.473	6.934	7.210	7.157	7.013	7.302
	P-value	0.000	0.360	0.009	0.016	0.122	0.003
Office	Participant	6.657	6.644	7.105	6.868	7.144	6.513
	System	6.710	6.381	6.578	6.723	6.789	6.763
	P-value	0.847	0.404	0.050	0.584	0.250	0.344
Aggre.	Participant	6.421	6.668	6.658	6.600	6.718	6.503
	System	6.979	6.716	6.879	6.797	6.832	6.937
	P-value	0.000	0.740	0.107	0.139	0.424	0.001

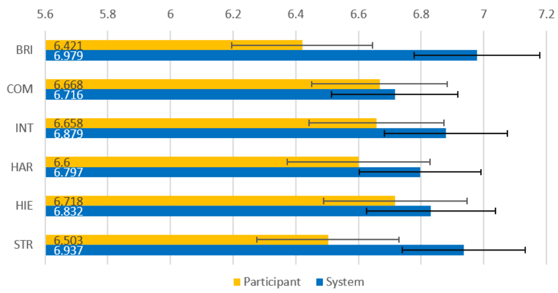


Figure 14: *Mean and confidence interval (95%) of each score for the lighting layouts made by our system and participants.*

out and the system's layout were similar for the living room and the office. In summary, the experiment showed that on average our system was better than or similar to the arrangement of the general user in terms of the functional, aesthetic, and structural criteria of the interior lighting guideline, but statistical significance was not confirmed to the all criteria.

5. Limitations and Future Work

We presented a system that automatically generates an optimized lighting layout in 3D indoor scenes based on the interior lighting guideline used in real-world interior design. This system creates lighting layouts in various room types, such as a private room, a living room, an office, and a studio, making individually optimized lighting layouts for each space. Nevertheless, our system has some limitations, which will be overcome by future research.

First, our system takes into account a number of major guidelines of the interior lighting design but does not consider some other guidelines, such as accent lighting, diffusers, and some indirect lighting practices. Incorporating such features will be an important future research direction. Second, we did not consider the effect of natural light entering through windows, but the natural light plays an important role in indoor illumination in daytime. Direct sunlight can be modeled as directional light of which incidence angle changing according to time while more sophisticated model would need to additionally include indirect lighting from an external environment. An additional cost term respecting a guideline that the object placement should not block natural light will help produce a harmonious arrangement. We assumed that all surfaces were diffuse material and did not consider specular and translucent materials, which are in fact common in the indoor environment. Consideration of such complex materials will improve the accuracy of predicting the effect of the indirect light. It will also help increase the quality of the lighting layout. For example, the system can avoid placing a light close to objects with a high reflection because it causes excessive glare. In this paper, we considered the general recommended illuminance for lighting arrangements, in particular for the indoor house and office environment. Our method can be applied to other types of environments, such as public lounge, if the pairwise relationship between the light and furniture is expanded to cover furniture in these environments. Another interesting future research direction is to develop an illumination recommendation and placement algorithm according to the user's mood by controlling the shape and intensity of the illumination.

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References

[DIA] DIAL GMBH: Dialux. https://www.dial.de/en/dialux/, Last accessed on 2018-07-25. 3

[eTe] ETEKS: Sweet home 3d. http://www.sweethome3d.com/, Last accessed on 2018-07-25. 3

[GP16] GKARAVELIS A., PAPAIOANNOU G.: Inverse lighting design using a coverage optimization strategy. *The Visual Computer 32*, 6-8 (2016), 771–780. 2

[GP18] GKARAVELIS A., PAPAIOANNOU G.: Light Optimization for Detail Highlighting. *Computer Graphics Forum 37*, 7 (2018). 2, 3

[GS09] GERMER T., SCHWARZ M.: Procedural arrangement of furniture for real-time walkthroughs. In *Computer Graphics Forum* (2009), vol. 28, Wiley Online Library, pp. 2068–2078. 2

[HFH16] HUANG S.-S., FU H., HU S.-M.: Structure guided interior scene synthesis via graph matching. *Graphical Models 85* (2016), 46–55. 2

[Ill11] ILLUMINATING ENGINEERING SOCIETY: *The Lighting Handbook, 10th Edition*, 2011. 2, 4

[KK] KÁN P., KAUFMANN H.: Automatic furniture arrangement using greedy cost minimization. 2

[KL17] KANG C., LEE S.-H.: Scene reconstruction and analysis from motion. *Graphical Models 94* (Nov. 2017), 25 – 37. 2

[LHH*13] LIN W.-C., HUANG T.-S., HO T.-C., CHEN Y.-T., CHUANG J.-H.: Interactive lighting design with hierarchical light representation. In *Computer Graphics Forum* (2013), vol. 32, Wiley Online Library, pp. 133–142. 2

[Lig] LIGHTING ANALYSTS: Agi32. https://lightinganalysts.com/, Last accessed on 2018-07-25. 3

[MSL*11] MERRELL P., SCHKUFZA E., LI Z., AGRAWALA M., KOLTUN V.: Interactive furniture layout using interior design guidelines. *ACM Trans. Graph. 30*, 4 (July 2011), 87:1–87:10. 2, 6

[NRM*12] NGUYEN C. H., RITSCHEL T., MYSZKOWSKI K., EISEMANN E., SEIDEL H.-P.: 3D Material Style Transfer. *Computer Graphics Forum (Proc. EUROGRAPHICS 2012) 2*, 31 (2012). 3

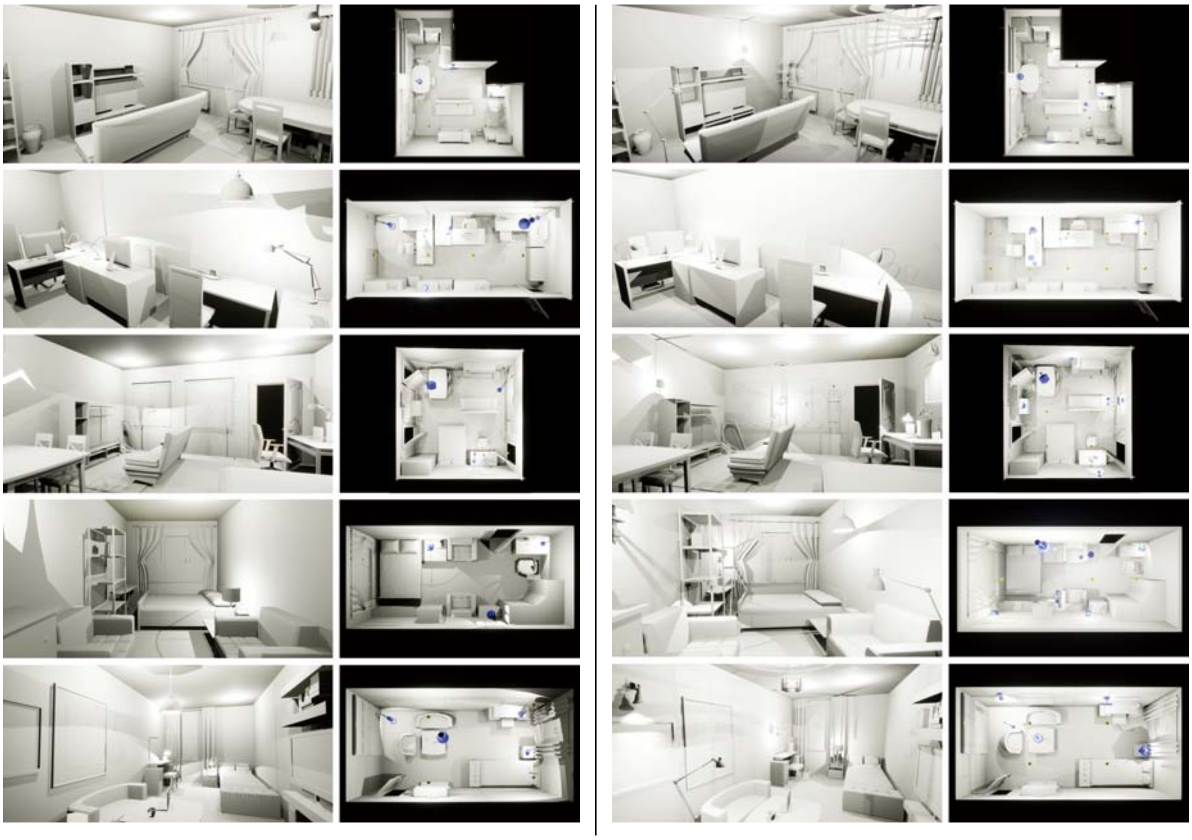

Figure 13: *Lighting layouts generated by participants (left) and by our method (right). From top to bottom: Living room, office, studio, private room #1, private room #2. These scenes, together with other scenes, were presented randomly to the participants for the perceptual evaluation.*

[OMSI07] OKABE M., MATSUSHITA Y., SHEN L., IGARASHI T.: Illumination brush: Interactive design of all-frequency lighting. In *Computer Graphics and Applications, 2007. PG'07. 15th Pacific Conference on* (2007), IEEE, pp. 171–180. 2

[Pan] PANASONIC.NET: The light required for each room. https://panasonic.net/ecosolutions/lighting/technology/knowledge/03/Last accessed on 2018-08-27,. 5

[PBMF07] PELLACINI F., BATTAGLIA F., MORLEY R. K., FINKELSTEIN A.: Lighting with paint. *ACM Transactions on Graphics (TOG) 26*, 2 (2007), 9. 2

[PP03] PATOW G., PUEYO X.: A Survey of Inverse Rendering Problems. *Computer Graphics Forum 22*, 4 (2003). 2

[Rel] RELUX INFORMATIK AG: Relux. https://reluxnet.relux.com/en/, Last accessed on 2018-07-25. 3

[SC07] SHESH A., CHEN B.: Crayon lighting: sketch-guided illumination of models. In *Proceedings of the 5th international conference on Computer graphics and interactive techniques in Australia and Southeast Asia* (2007), ACM, pp. 95–102. 2

[SDS*93] SCHOENEMAN C., DORSEY J., SMITS B., ARVO J., GREENBERG D.: Painting with light. In *Proceedings of the 20th annual conference on Computer graphics and interactive techniques* (1993), ACM, pp. 143–146. 2

[SOL*16] SORGER J., ORTNER T., LUKSCH C., SCHWÄRZLER M., GRÖLLER E., PIRINGER H.: Litevis: integrated visualization for simulation-based decision support in lighting design. *IEEE Transactions on Visualization and Computer Graphics 22*, 1 (2016), 290–299. 3

[SW14] SCHWARZ M., WONKA P.: Procedural design of exterior lighting for buildings with complex constraints. *ACM Transactions on Graphics (TOG) 33*, 5 (2014), 166. 2

[SYZ*17] SONG S., YU F., ZENG A., CHANG A. X., SAVVA M., FUNKHOUSER T.: Semantic scene completion from a single depth image. *IEEE Conference on Computer Vision and Pattern Recognition* (2017). 1, 8

[UAB] UAB PLANNER 5D: Planner 5d. https://planner5d.com/, Last accessed on 2018-07-25. 3

[XMZ*14] XU K., MA R., ZHANG H., ZHU C., SHAMIR A., COHEN-OR D., HUANG H.: Organizing heterogeneous scene collections through contextual focal points. *ACM Trans. Graph. 33*, 4 (July 2014), 35:1–35:12. 2, 6

[XSF02] XU K., STEWART J., FIUME E.: Constraint-based automatic placement for scene composition. In *Proceedings of the Graphics Interface 2002 Conference, May 27-29, 2002, Calgary, Alberta, Canada* (May 2002), pp. 25–34. 2

[YDY16] YAMAKAWA T., DOBASHI Y., YAMAMOTO T.: Efficient simulation of furniture layout taking into account lighting environment. In *Proceedings of the 29th International Conference on Computer Animation and Social Agents* (2016), ACM, pp. 173–179. 3

[YYT*11] YU L.-F., YEUNG S.-K., TANG C.-K., TERZOPOULOS D., CHAN T. F., OSHER S. J.: Make it home: Automatic optimization of furniture arrangement. *ACM Trans. Graph. 30*, 4 (July 2011), 86:1–86:12. 2