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Light and Lighting

A toolbox for volumetric visualization of light properties

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In this paper, we introduce a toolbox for the perceptually based visualization of light in a volume, focusing on the visual effects of illumination. First, our visualizations extend the conventional methods from a two-dimensional representation on surfaces to the whole volume of a scene. Second, we extend the conventional methods from showing only light intensity to visualizing three light properties (mean illuminance, primary direction and diffuseness). To make our methods generally available and easily accessible, we provide a web-based tool, to which everybody can upload data, measured by a cubic or simple illuminance meter or even a smartphone-app, and generate a variety of three-dimensional visualizations of the light field. The importance of considering the light field in its full complexity (and thus as a three-dimensional vector field instead of its two-dimensional sections) is widely acknowledged. Our toolbox allows easy access to sophisticated methods for analysing the spatial distribution of light and its primary qualities as well as how they vary throughout space. It is our hope that our results raise interest in ‘third stage’ approaches to lighting research and design, and the toolbox offers a practical solution to this complex problem.

1. Introduction

Illumination visualization plays an important role in evaluating a lighting design of a space or a building. An image or a schematic representation of a scene provides designers with an instant grasp of the information, whereas descriptive texts or data tables are more likely to require effort for interpretation. As a Russian proverb says, ‘*better to see something once than to hear about it a hundred times*’.

One of the common methods of showing scene illumination is a straightforward rendering of light in a scene via sketching or a

computer-generated image. Sketching lighting on paper or in software is a fast way for capturing and communicating lighting ideas.¹ It can show shapes of light beams or identify objects and surfaces which require to be lit.² However, this approach does not allow and does not aim to produce an accurate representation of light in a scene,³ so it is mostly suitable for the early stages in the design process.⁴ A photorealistic rendering, on the other hand, gives a glimpse of how a lighting design will look as a final result. However, such rendering also has disadvantages such as a narrow dynamic range of the resulting image and extensive time required to produce renderings.¹ Murdoch *et al.*⁵ have demonstrated how difficult it is to estimate the brightness of the illumination in a modelled scene, showing that an image of a dimly lit room is often judged as an underexposed

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image of a normally lit room. Additionally, such images show only how lighting affects scene walls, floors and ceilings plus the objects which are already placed in the scene. This might be not enough if, for example, a final arrangement of furniture is not yet known. Nor does it represent the visual experience of a user who moves through such a scene.

For a more accurate examination of an illumination design, light professionals use visualizations based on light measurements. The most common of those is a false colour image (see Figure 1) that encodes luminance/illuminance values on all visible surfaces^{6,7} or planes of interest (Autodesk 3ds Max Lighting Analysis Assistant (LAA); DIVA⁸). False colour visualizations allow a designer to assess the illuminances in order to, for instance, check whether they satisfy lighting standards. These standards set illuminance requirements including minimal illuminances on horizontal and vertical planes.

There is a growing conviction that the focus of the lighting profession (and, therefore, lighting standards and light visualization methods) will be extended beyond illumination on planes to light in three-dimensional (3D) volumes (see Section 2.1). Additionally, the illuminance is not the only light property influencing the appearance of objects and spaces. Thus, other light properties might be

also worthy of visualizing explicitly (see Section 2.2). Our interactive tool fills these gaps by providing a method for volumetric visualization of multiple light properties (mean illuminance, direction and diffuseness) simultaneously.

In the next section, we further explain the motivation for creating our tool and list previous work. In Section 3, we describe the light visualization tool and provide examples of its application for lighting design. Section 4 contains insights on volumetric physical measurements, including a comparison of the visualizations obtained via three physical measuring tools that vary in precision – including a method that allows general use of our toolbox with smartphone measurements.

2. Motivation and previous work

2.1. From surfaces to volumes

There are many situations in which a researcher or designer might need information about light in (empty) space. For example, in studies on daylight and glare (see examples in references^{9–11}), measurements are often made at a position where a person is expected to be seated. Indeed, in many cases an employee spends the majority of time in almost the same position. However, this approach does not suit open spaces where employees can change their positions around, or meeting rooms where



Figure 1 The leftmost image shows a scene, the middle image is a false colour representation of the illuminance over all surfaces of a scene, the right image is a false colour representation of the illuminance over planar cross-sections in the space (available in colour in online version)

seating positions are not strictly arranged or any space where humans move around (shops, museums, sport halls or even outside spaces). In these cases, there is a need for multiple measurements within the spaces. Lam¹² criticized conventional lighting approaches for isolating the task of reading a carbon copy, which was outdated a long time ago, as the basis for lighting everywhere in an illuminated space. Obviously, human activities vary in tools, time and position over spaces. He also stated that the criteria for a lighting design should not only be about eliminating negative elements, e.g. visual discomfort, but also about providing positive aspects of the luminous environment. The latter can be achieved by considering expected activities in a designed space and ‘biological information need’, the need for information coming from the surrounding visual environment. Boyce^{13,14} agreed that following existing guidelines will usually ensure avoiding poor-quality lighting, but will do little to ensure good-quality lighting. Cuttle *et al.*^{15,16} suggested that the next development stage of the lighting profession requires that instead of accounting for the light on surfaces, designers should consider light arriving at the observer’s eye. In order to capture a full description of all light in a space that may potentially arrive at an observer’s eye, we need a human-centred or perception-based description of the light field that is the light as a function of position and direction.^{17,18}

Another reason for visualization of light in a volume is that it might be difficult to see at a glance which component of a design produced a certain light effect while working with complex spatial geometries and multiple light sources. Psychophysical studies show that human observers are able to infer light fields, but their impression seems to be simplified with respect to the real physical distribution of light in a scene.^{19–21} Therefore, a simplified volumetric visualization could be helpful for a better understanding of light in space.

Light travels in every direction through every (transparent) point. This feature makes it difficult to visualize or even describe all information resulting from the interaction of light with the geometry and material in a 3D space. A solution for this was first proposed by Gershun¹⁸ by introducing the concept of the light field, a five-dimensional function determining the radiance arriving at a point x, y, z from directions θ, φ . In our implementations, we use luminance instead of radiance because we are interested in the visual appearance of light. Additionally, he defined the light vector as the net transport of radiant power (in other words: the average luminance direction). Cuttle¹⁵ proposed a panoramic (‘field of view’) imaging for capturing the light field in a point. Yet, in order to measure an entire light field one would have to make spherical photographs in every point of a measured volume. Doing so would require an impossible amount of labour and storage place, and also it is not clear how all this information could be used. Moreover, as mentioned before, humans seem to have a simplified impression of the light field, thus we do not need the full approach. Later, Mury *et al.*²² developed Gershun’s concept further, finding that the lower order components of physical light fields (equivalent to ambient and directed light plus squash tensor) vary smoothly over spaces and therefore can be reconstructed using relatively few measurement points and interpolation to obtain values in-between measurements.

Lighting design researchers have studied light in a 3D volume using the concept of light flow. Lynes *et al.*²³ recommended the scalar and vector illumination for analysing the structure of light. They visualized the flow of light via lines of flow that show (variations of) the light direction for a cross-section in a space (see example in Figure 2). The authors emphasized that the flow lines are not rays of light; thus, there is no contradiction between light traveling in straight lines and a flow line

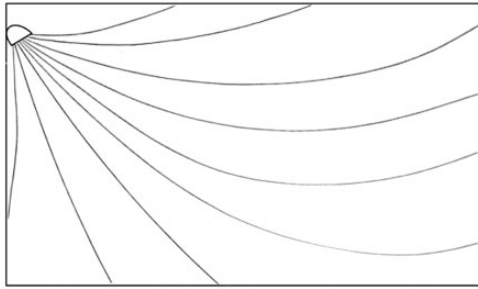


Figure 2 A drawing of lines of flow for a single light source in the top left corner of a room. The room is empty with walls and ceiling covered with a diffuse material that reflects some portion of light. The lines are slightly curved because of light reflection from the floor

being curved. The reason is that flow lines in any point in space represent the average direction of all rays, similar to the ‘lines of force’ for magnetic fields. Cuttle^{24,25} explained the influence of the light flow and sharpness of light on object appearance, where the first concept describes the strength and direction of light and the second reflects shadows and highlights patterns. Dale *et al.*²⁶ proposed an elegant method for determining the direction of a light vector using two pieces of paper, both marked with a wax creating a translucent spot. These pieces of paper were mounted on a stick perpendicularly to each other. For each paper holds that if the direction of the light vector was in the plane of the paper, the grease spot looked equally bright as the surrounding paper because the illuminance on both sides would then be equal. Thus, when both spots ‘disappeared’, the stick was aligned with the light vector in that spot. Interestingly, without an evident relation to lighting design research, physicists came up with an idea very similar to light flow. Wu^{nscher et al.²⁷ called it the energy flow (of light) and visualized it as vectors or stream lines. They also related the concept to the structure of electric fields, thus applying similar rules to (light) energy flow lines: they never cross one another, they originate on light sources and end on absorbers, and they}

run parallel to a reflecting surface in their immediate vicinity.

In all the studies mentioned above, the visualizations were restricted to cross-sections through spaces. Until recently, it was not possible to produce 3D visualizations for the quite extensive data sets that a full light field usually encompasses because the technical possibilities simply were not available. But with the development of computing, modelling and visualization technologies, it has become possible to create complex 3D models leading to a new leap of development on light in volumes. In light field research, researchers measured the virtual light field,²⁸ modelled and visualized the light field as density and vector field plots,²⁹ presented light direction and mean illuminance as a grid of arrows of varying size,³⁰ and visualized light flow as light tubes.^{31,32} In computer graphics, striving for realism stimulated the development of illumination algorithms.^{33–36} Studies in this field visualized light rays^{37,38} avoiding clutter,³⁹ and showed various light properties.^{30,40,41} Although the listed studies demonstrate a variety of light visualization methods, they are mostly targeted at the computer graphics audience and often take advantage of rendering methods. It makes them difficult or sometimes even impossible to apply for physical measurements.

In our toolbox, volumetric visualization of the light field is based on Mury *et al.*'s³¹ grid measurement approach, simplified by using Cuttle's^{17,42} formulas for cubic measurements. The resulting method is much simpler with regard to the measurements and calculations than most of the methods listed above and allows efficient and robust reconstructions of the variations of light properties over either physical or virtual 3D space. The main difficulty of our method lies in the steps that need to be taken from raw data to the actual 3D visualizations, for which we provide our web-based publicly available tool.

2.2. Showing multiple light properties

It is impossible to have a meaningful visualization of light while preserving all the information of the light field because there are infinitely many light rays passing through every point of (empty) space. However, it is possible to extract a few important features/properties and visualize their variation. The next question is, which light properties are important?

The mean illuminance, direction and diffuseness are the main properties that appear in the literature on lighting design,^{3,4,6,17,43,44} computer graphics,^{45,46} photography and drawing.^{47,48} In visual perception studies, results showed that human observers are highly sensitive to the mean illuminance, diffuseness and average direction of light, not only on surfaces but also in empty space.^{19,20,49–52} Often, authors use different terms to describe those light properties, but it is usually clear that the authors mean the same quality. For example, diffuseness,²⁰ softness⁴⁵ and contrast⁴⁷ all seem to describe the same basic property of light, namely the ratio between the directed and ambient light.

Based on the above-mentioned considerations, we chose to visualize the (variations of) values of mean illuminance, direction and diffuseness of the light, introduced in this combination by Xia *et al.*^{32,53} We did this via shapes and variation of their proportions. In order to obtain the values of the light properties, we use Cuttle's^{17,42} approach of cubic illuminance adopted for multiple measurements, physical^{19,32,53} as well as virtual.⁵⁴

3. Visualization toolbox

3.1. Overview

The algorithms constituting the visualization toolbox are explained in detail in Kartashova *et al.*,⁵⁴ and here we will provide a general description of the key features of the toolbox. It contains two main components.

For each measurement position, the first component translates the input of six cubic light measurements into the following three light properties: mean or scalar illuminance, strength and direction of the light vector, and diffuseness (ranging from 0, fully collimated light, to 1, fully diffuse light). The second component creates the resulting visualizations by expressing the values of these light properties through varying the proportions of various shapes (arrows, ellipses and tubes). The resulting visualizations were psychophysically evaluated by Kartashova *et al.*⁵⁴

The arrows visualization adapts Jacobs'³⁰ representation of light vectors pointing at the direction where the light comes from for every point of a vector grid. It is important to note that the chosen direction is that of the illumination, which is actually the physically important quantity – such that the component of the light vector in the direction of the surface normal of any given surface element represents the net flux density.^{18,22,55} We visualize the mean illuminance via the arrow length, and the diffuseness via the width of the arrow shaft: the thicker the shaft, the more diffuse (less directed) the light is. The diffuseness judgments do not suffer from perspective distortion, since the arrowhead is always of the same size whereas the ratio of the arrowhead size and the shaft thickness varies.

The second type is visualization using ellipsoids.⁵⁶ The long axis orientation of an ellipsoid is aligned with the light vector. The size of each ellipsoid corresponds to the mean illuminance. The proportion between the short and long axes corresponds to the diffuseness. The more elongated the ellipsoid is, the more directed (lower in diffuseness) the light is. Fully diffuse light does not have a dominant direction, and is thus represented by a sphere.

The third type of visualization is done via light tubes.³¹ A tube is locally tangential to the light vector, and in our visualizations its

width is inversely proportional to the mean illuminance (in Gershun's¹⁸ and Mury *et al.*'s³¹ approach, its width was inversely proportional to the strength of the light vector). The intuition behind this choice comes from fluid flow representations: the smaller the tube, the faster/stronger the flow. The set of tubes represents the 'light flow'²⁵ and often shows a structure diverging out from the source to light absorbing surfaces.^{19,31} These 'superpatterns' can also be seen in the vector and ellipsoid visualizations

as a global structure formed by the ensembles of shapes.

Figure 3 demonstrates these shapes and their variations when visualizing several light conditions, plus photographs of a white sphere in those conditions – to show the relation with how objects appear in those conditions – since this is usually what we see and how we judge the light in realistic contexts. For arrows and ellipsoids, the first and second columns of images show differences in mean illuminance, the first and third

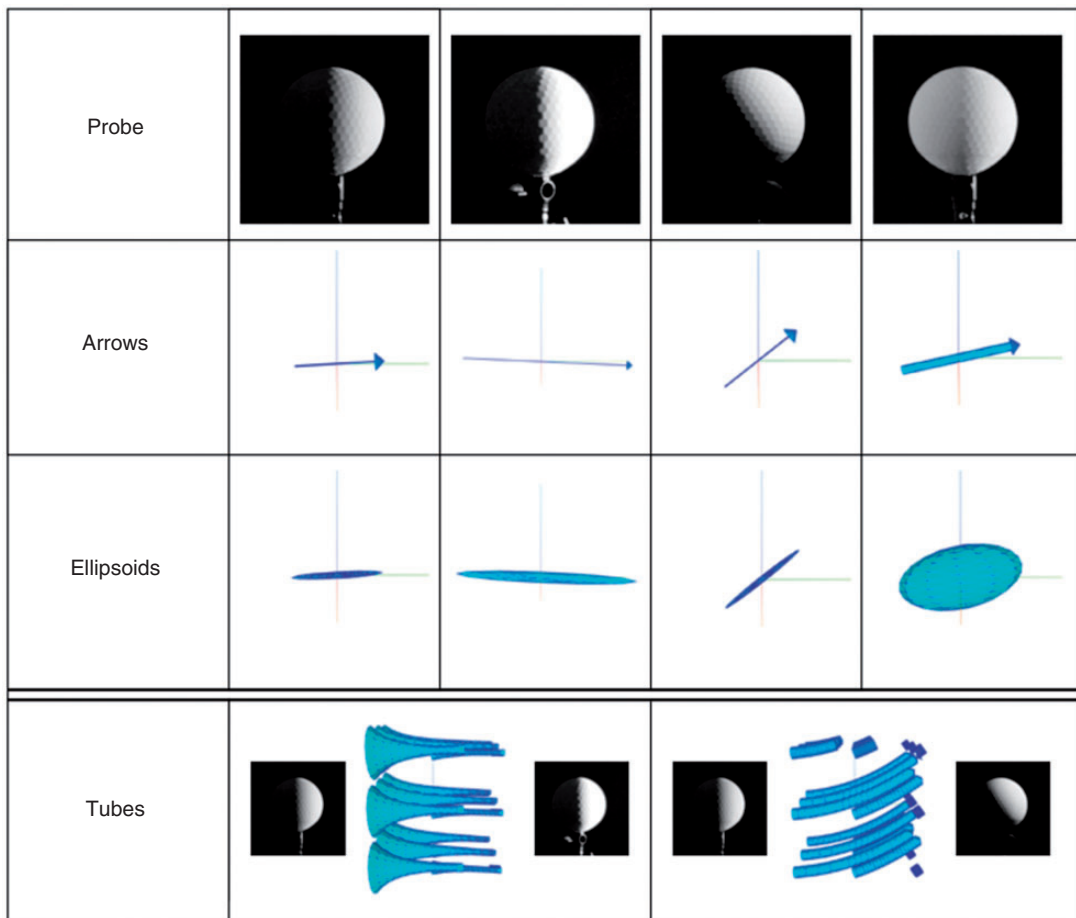


Figure 3 Examples of shapes' visualizations and photographs of various light conditions. Note that the arrow and ellipsoid in the column with the strongly directionally illuminated sphere are scaled at half the other shapes to show the whole visualization

columns show differences in direction, and the first and fourth show differences in diffuseness. The slight differences in direction between columns one, two and four are due to a real scene being used for the measurements and photographs. The inter-reflections and slight variations between light source and the probe positions influence the resulting light direction. The tubes illustrate the variation of the parameters over the volume, with variation of the mean illuminance in the first column and variation of the direction in the second column.

We evaluated the visualizations via a user test.⁵⁴ Participants were first asked to compare the light properties between three positions in scenes and secondly to match the appearance of illuminated objects to their positions in three scenes. Both tasks were performed using scene renderings and each of the visualizations. The main result was that all the visualizations gave better or not significantly different performance compared to the renderings. We did not compare the visualizations between each other because the goal of the study was to test the performance of the introduced tool compared to renderings. Moreover, an informal survey with our participants suggested that the choice of shape type was probably a matter of personal preference.

In order to demonstrate the visualizations in action and make our tool available for everybody, we created a web-based visualization toolbox. It lets the user load files of light measurements or to pick example data files, and transform the data into interactive 3D visualizations.

3.2. Workflow

The workflow of the tool is the following (Figure 4). After loading the webpage (Figure 5, the provisional link to access the tool is <http://lightvisualizations.000webhostapp.com/>). We will place the tool at the lab page before the publication to see [\[tatianakartashova.me/light-visualization-tool/\]\(https://tatianakartashova.me/light-visualization-tool/\) one should load a light measurements file or pick one of the example measurements files from the list. The light measurements file should be comma-separated and saved with the corresponding extension \(*.csv\). Every line represents a measurement point containing six illuminance measurements \(one on every side of a cube\) and the three coordinates of the measurement point in space. See details of the measurement procedure in Section 3. If the file format is correct, the webpage will immediately show a visualization. The interface allows changing the viewing direction and zooming in/out using mouse click-and-drag and centre wheel, respectively.](https://</p>
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Next, one should address if the measurements were done with a cube which was oriented normally (sides of the cube faced according to the XYZ axes) or diagonally (one of the main diagonals of the cube is oriented vertically) (Figure 6). If the measurements were made with a diagonally oriented cube, a tick should be placed in the ‘Diagonal cube’ tick box. Then a shape type can be chosen (by default it is arrows). Note that if the measurement grid is not regular, the demo cannot produce tubes because of the interpolation difficulties of that particular case.

The resulting visualizations may be adjusted. They can be rotated by the mouse or touchpad using dragging and dropping, and they can be zoomed in or out using scrolling. All shapes may be scaled using the ‘Shapes scale’ slider. This determines the size of the ellipsoids, the lengths of the arrows’ shafts and the widths of the tubes. By default, the coordinate origin (centre of rotation) is placed in the centre of the measured volume. It can be placed according to the measurements’ origin by removing a tick in the ‘Centre visualizations’ tick box. The tubes visualization has its own adjustment menu. There, one can choose step size, number of steps and number of tubes on each axis. Step

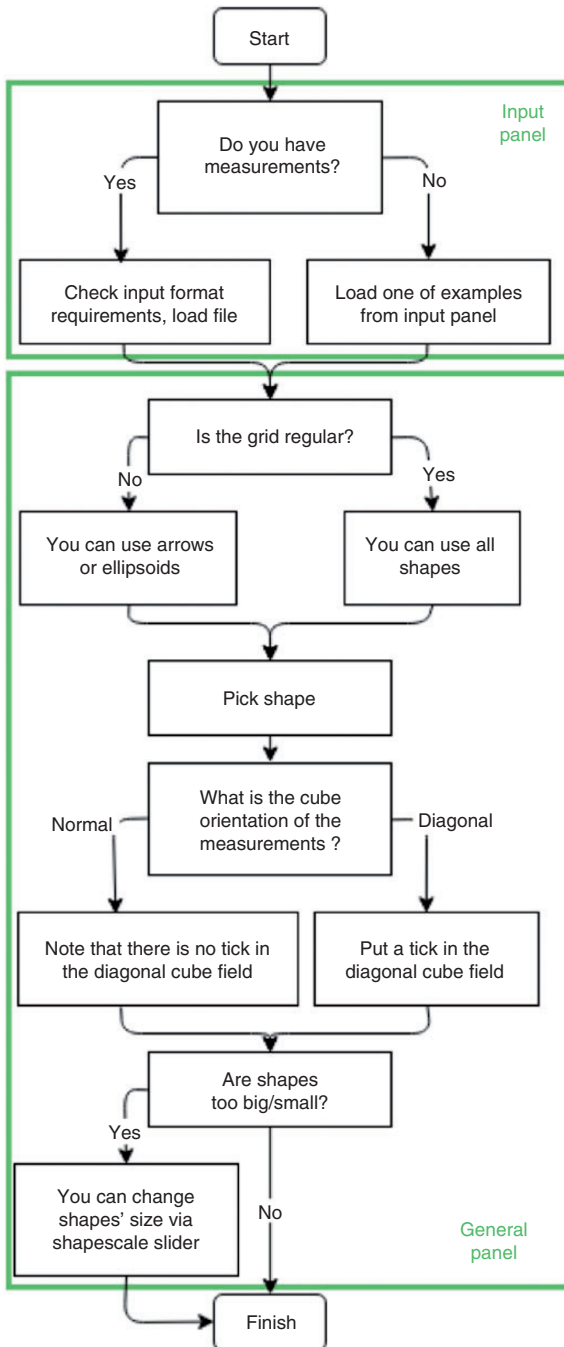


Figure 4 Workflow of interaction with the user. First, the user is supposed to upload his/her own measurements or one of the provided examples, then select and adjust shapes in order to show the variations of the light properties in the best way

size regulates the size of the steps between the points of the tubes at every interpolation point. It is important to note that the starting points of the tubes are placed such that the tubes originating on the edge of the volume can make at least one step within the measured volume. The number of steps regulates how many points will be calculated for each tube.

3.3. Visualization examples

In this section, we present two examples of the practical use of our visualizations toolbox. The first example demonstrates the influence of scene content on the resulting light field in the volume of the scene. The second example shows daylight measurements visualizations for two different sky conditions.

The scene for the first example was constructed in a laboratory with no windows and a single light source. One wall was always black, another was black for one set of measurements and white for another. The third side was covered with a black curtain, which also occluded the light source from a part of the measured volume. The fourth side was open to an unilluminated part of the room which was not included in the measurements. The ceiling was white and the floor was black. We measured a grid of four points in width and length and three points in height (Figure 7). The grid was 2 m in width and length. Measurements were taken at heights of 1.0 , 1.5 and 2.0 m from the floor. We used a Konica Minolta T-10MA illuminance meter with six mini sensor heads placed on a cube (see more in Section 4).

Figure 8 shows photographs of the measured scene, left for the black and right for the white wall condition, produced with the same camera settings. It is clear from the enlarged white spherical probes below the scene images that the white wall dramatically changes the light conditions in the room (note that the light source and camera exposure were the same).

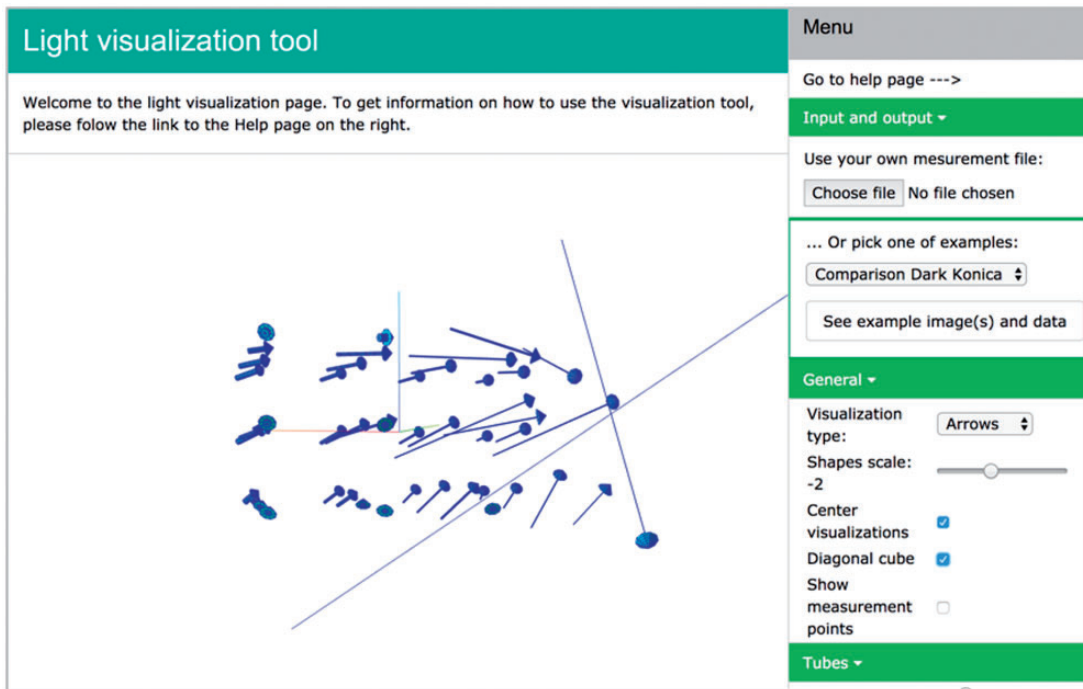


Figure 5 Light visualization interface. Most of the webpage is taken by an interactive view of the visualization. On the right is the menu for loading and controlling the visualization

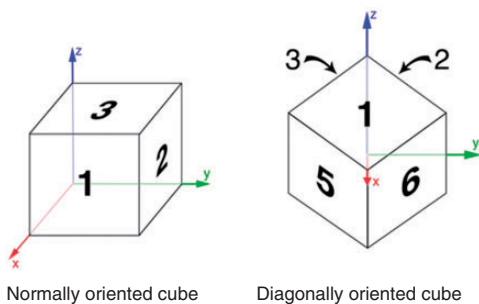


Figure 6 Two possible orientations of the cubic illuminance measurements

Figure 9 demonstrates the visualizations of the measurements for both scenes. Close to the light source arrows do not seem to differ between the scenes whereas the remainder of the arrows in the white wall condition are longer and thicker than the ones in the dark

wall condition. This is because the white wall reflected more light than the dark wall and made the light in the scene denser and more diffuse. Additionally, the arrows in the left side of the grid, closest to the wall, show dissimilar directions in the scenes because the reflected light influenced the average light direction in those points. Thus, the visualizations here give clear insights into the complex effects of material–light interactions and how these affect the structure of the light field.

For the second example, we measured an office room illuminated with daylight. We measured a grid of three points in the width, four points in the depth of the room with respect to the window and three points in the height (Figure 10). The grid was 1.2 m in width, 2.4 m in length. Measurements were taken at heights of 1.0, 1.5 and 2.0 m

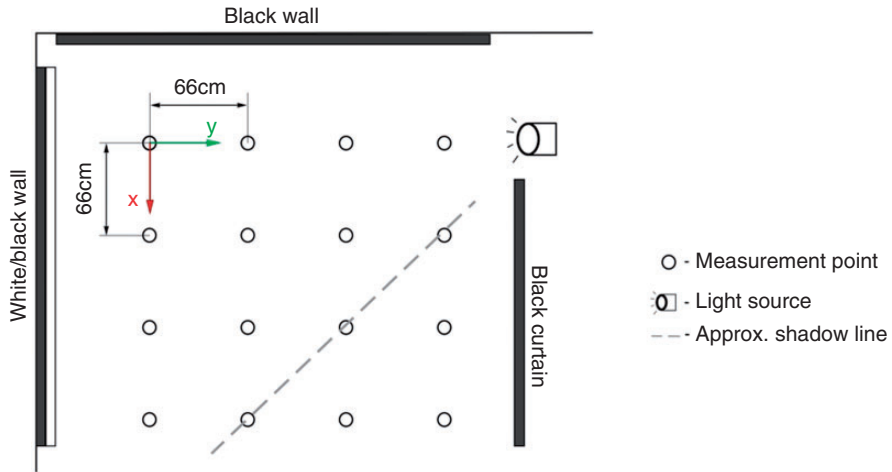


Figure 7 Example one. Room scheme, top view

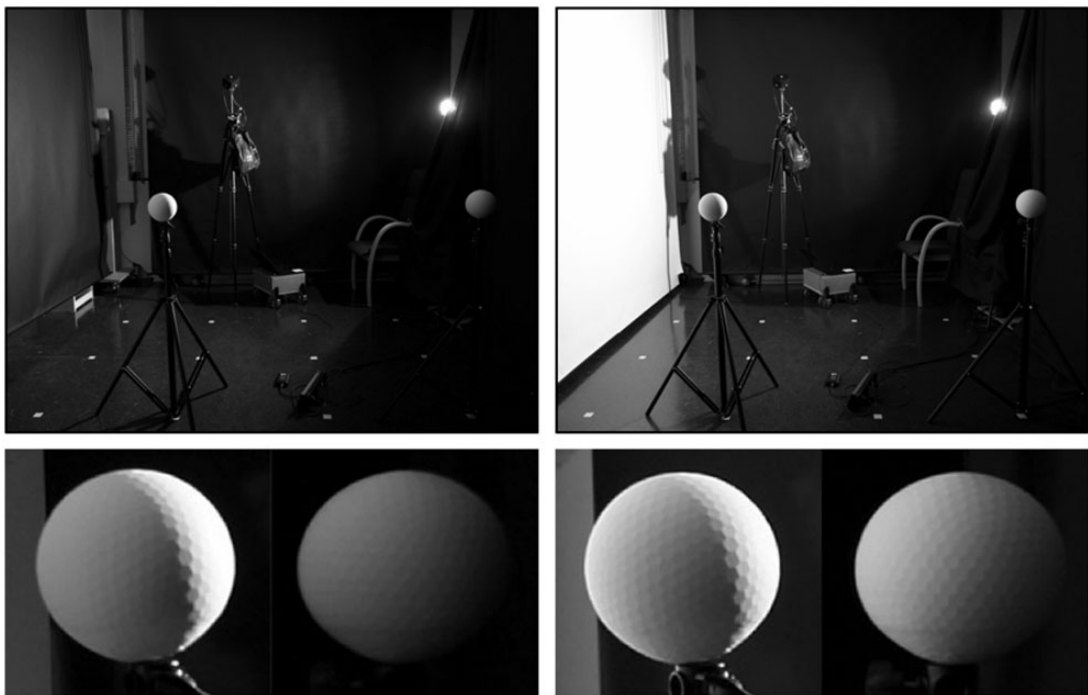


Figure 8 Example one. Room and light probe photographs

from the floor. The measurements were made at roughly the same time of the day, on two days with different weather. One day it was sunny (Figure 11, left), the other day it was

rainy with the sky fully covered with clouds (Figure 11, right). Measurements on the sunny day were made between 15:06 and 15:21, on the rainy day between 15:22

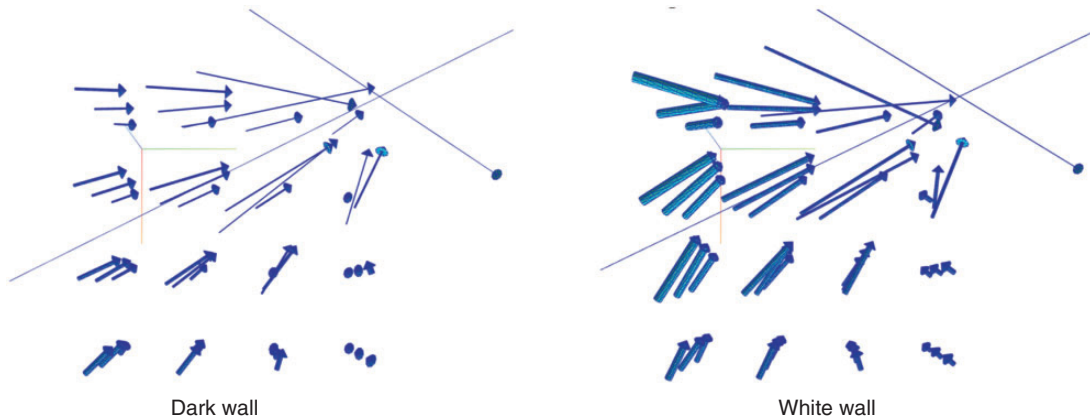


Figure 9 Example one. Arrows visualizations of the measurements for dark and white walls, from a top view as in Figure 7. Note the difference in lengths, directions and thickness of the arrows

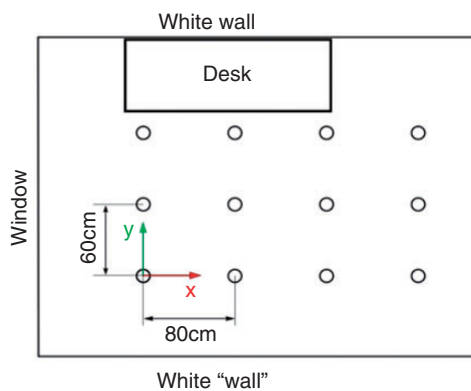


Figure 10 Example two. Room scheme

and 15:40. Note that the photographs of the room were made with different camera settings because the dramatically different lighting conditions made it impossible to capture photographs at the same exposure level. To evaluate the difference, one can take into account the fact that the brightness of the laptop screen was the same between conditions. The laptop screen on the left image of Figure 11 looks dim, it is completely over-exposed on the right image.

Similar to the photographs, the measurements are also presented with different scales

because for the sunny scene (Figure 12, left column) the resulting mean illuminances ranged between 945 lux and 9338 lux, yet for the rainy one (Figure 12, right column) the range was between 22 lux and 102 lux. The tube images show the light field from a top and side view, with the window at the left side. There are clear differences in the structures of the light fields between the conditions. The measurements of the sunny scene have two distinct parts. Most of the scene was illuminated with strongly directed sunlight, except for the volume close to the ceiling and the volume far away from the window in depth of the room, which were occluded from the sun. The thin, uniformly directed tubes illustrate that the sunlit part has strongly directed light from the window at the left of the figure (Figure 12, left column). The sunlight-occluded part of the scene results in much thicker tubes – lower light densities – and light directions at large angles to the sunlit part due to light reflected from the wall on the left (see also the light gradient on the ceiling in Figure 11, left). In contrast, the rainy scene represents rather uniform illumination with a smooth gradient in the mean illuminance from the window to the back of the room. As a result, for example, the white

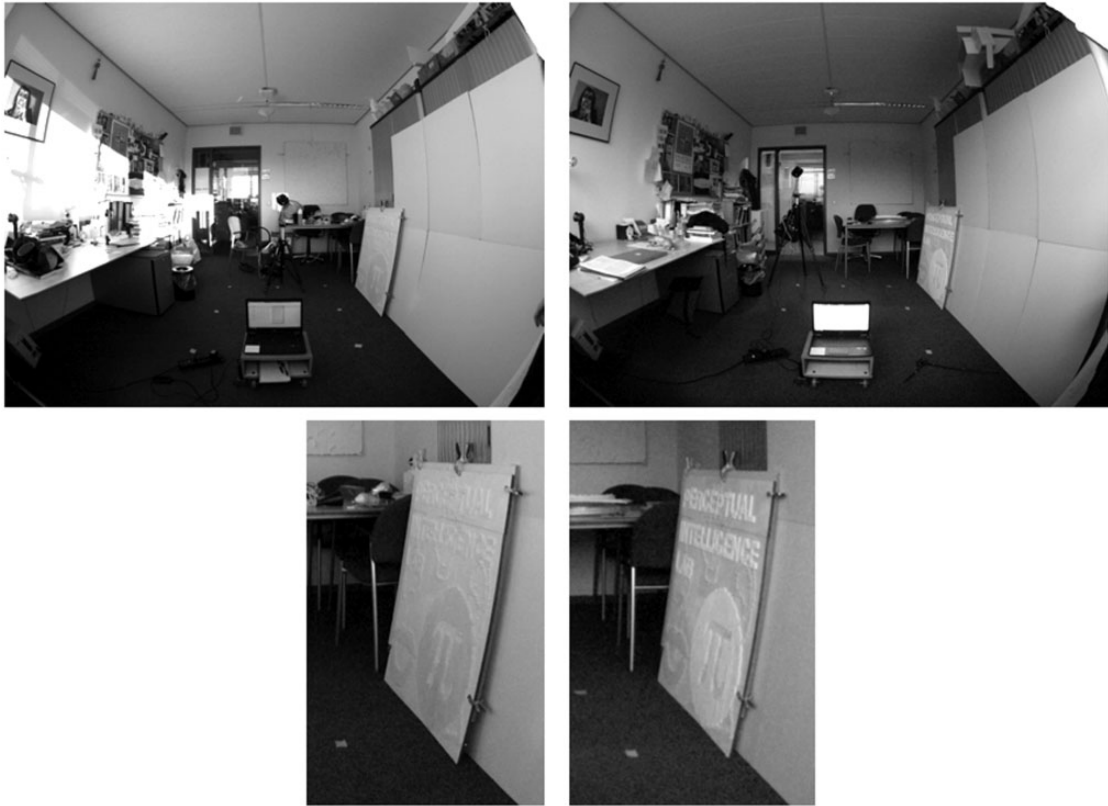


Figure 11 Example two. Top row: room photographs. Left the sunny condition and right the overcast sky condition. The room-width window is behind the photographer. Bottom row: enlarged relief panels, note the difference in appearance

relief with π symbol in the back right of the room (enlarged in Figure 11, bottom row) is illuminated differently between conditions which results in dramatic differences in its appearance.

We have demonstrated that our visualizations provide strong support to an understanding of variations of light over spaces for several examples of illumination. Moreover, they make it possible to see subtle light effects throughout the empty space in a glance, which cannot be fully captured from the photographs. We believe that these analyses might also help to understand interactions between lighting (artificial plus daylighting) and a scene geometry as well as the dynamics

resulting from combinations of artificial and (varying) daylighting.

4. Volumetric light measurements

4.1. Comparison of the three measurement devices

Here, we compare measurement visualizations for three tools with varying precision (Figure 13) in order to see to what extent a tool precision influences the resulting visualization. The first device was a cubic meter³² based on a Konica Minolta T-10MA illuminance meter with six mini sensors heads connected together for cubic measurements.

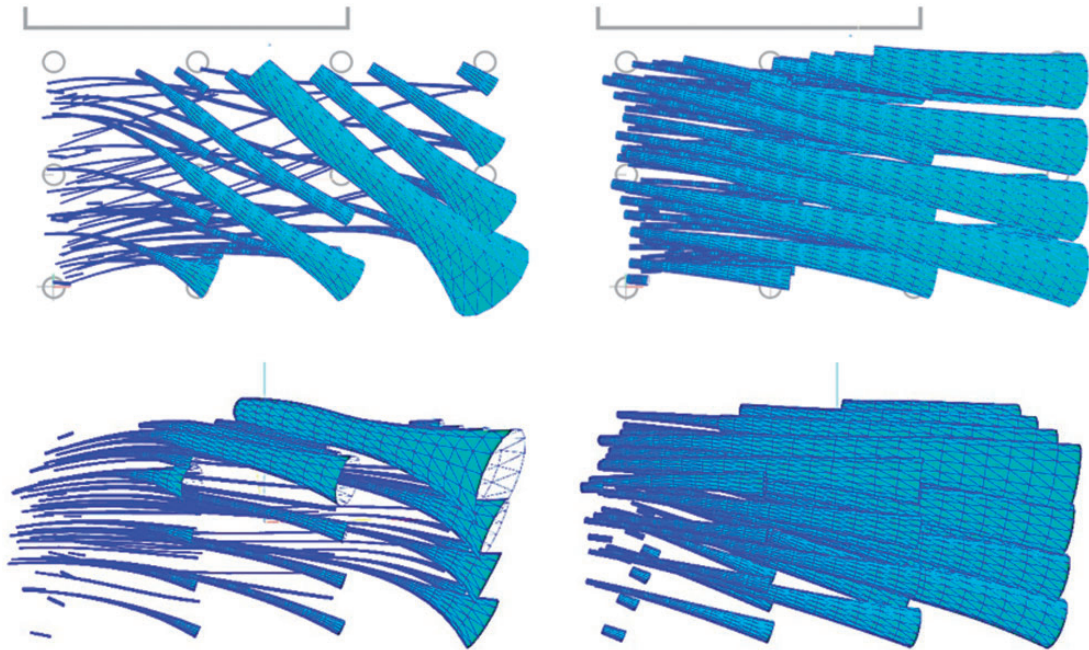


Figure 12 Example two. Tubes visualizations of the measurements. The first row shows top views as in Figure 10. The second row shows side views, with the window on the left. The left column shows the light flow for the sunny scene, the right for the rainy scene



Figure 13 Measurement devices. Left to right: cubic meter based on the Konica Minolta system,^{32,53} luxmeter and smartphone with Luxi

Thus, the device provided simultaneous measurements of all six sensors. The second device was rather cheap, a common luxmeter (Voltcraft MS-1300) with a single sensor.

We made cubic measurements with this device by placing it consecutively on the six faces of a cube and recording its output values. The third device was a smartphone

with a white diffusion cap (Luxi) and the corresponding app (see measurements evaluation study by Gutierrez-Martinez *et al.*⁵⁷). We used the Luxi for cubic measurements in the same manner as the luxmeter. Of these three devices, the cubic meter has the highest accuracy and the Luxi the lowest. The same order applies to the price of the devices, ranging from a few thousands of Euro's for the Konica Minolta system to around 30 Euro for the Luxi.

The measurements were performed in the black wall scene described in Section 3.3 (Figure 7 and Figure 8, left). We compared deviations of light properties between the Konica Minolta system as baseline and the two other devices. The results are presented in Table 1. For direction, we calculated the angular difference between the light vectors. For mean illuminance and diffuseness, we calculated the absolute difference between the measurements. Maximum deviations for the mean illuminance occur close to the light source where large differences occur between the light emitted in different directions. The range of mean illuminances in the room, according to the Konica Minolta device, was between 34.51 and 13 500 lux. As one could expect, all median deviations for the common luxmeter are lower than for the Luxi, for all parameters.

Visualizations of the measurements are presented in Figure 14. The cubic illuminance meter and luxmeter produced visually similar results. The luxmeter visualizations have barely noticeable deviations in the pattern, which are almost entirely averaged out by the tubes' visualization. The individual Luxi results are considerably noisier, as expected, but as a set they still produce a similar pattern, which make it possible to see the flow of light through the scene. In the tubes visualizations, it can be seen that with noisier data the variations in the tube shapes become somewhat noisier, yet the main structure stays the same. Thus, the light field structure can be

measured robustly, even with extremely cheap devices. This result, plus our publicly available tool, now allow anybody to measure and visualize the structure of the light throughout any space. In this way, we hope to support the lighting profession in its third stage.¹⁵

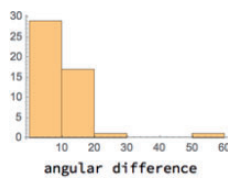
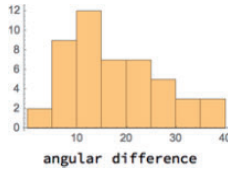
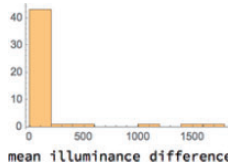
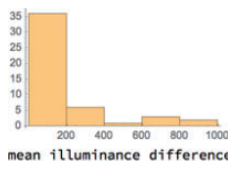
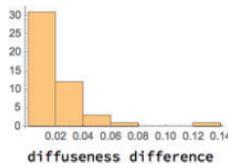
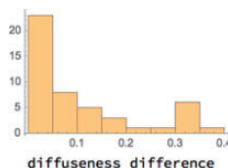
4.2. Recommendations for measurements

In Section 3.1, we described the requirements for the input file content. This section contains practical recommendations for making measurements. Making a grid of physical cubic measurements might seem labour-intensive. However, after some practice, even measurements taken with a single lux meter (as in Section 4.1) might take less than half a minute per point (=6 measurements). Moreover, even measurements for a single point can be visualized using the arrows or ellipsoids, whereas the tubes' images may be created based on a minimum of a $2 \times 2 \times 2$ measurements grid. If the light field is expected to be complex (for instance because there are many light sources and occlusions), more measurements are needed to reflect its structure variations than in the case of a simple light field (for instance, a single light source in relatively empty space).

One approach to produce a grid of measurements consists of the following actions:

- Pick the size of the measurement volume and the number of measurements to be made over each axis. It is useful to mark the measurement positions on the floor.
- Set up the measurement device and a table for keeping measurement records. Besides that, it is necessary to prepare the device, e.g. install the corresponding software and calibrate the device. The table serves for saving the illuminance measurements and position coordinates.
- Taking the measurements. In order to minimize the disturbance of measurements by being present in the scene, it is suggested to avoid occluding main and secondary light sources from the sensors. We achieved

Table 1 Deviations of the resulting properties measurements between the common luxmeter-based device and baseline and between the Luxi-based device and baseline

Property	Device	Median	Min	Max	Histogram
Direction (angular difference, degrees)	Common luxmeter	8.44	2.75	51.94	
	Luxi	16.52	2.73	38.35	
Mean illuminance (lux)	Common luxmeter	61.76	1.56	1666.8	
	Luxi	103.14	6.24	900.89	
Diffuseness (diffuseness scale, ranges from 0 to 1)	Common luxmeter	0.013	0.001	0.122	
	Luxi	0.055	0.001	0.354	

Note: The baseline properties were obtained from measurements made with a Konica Minolta-based cubic illuminance meter.

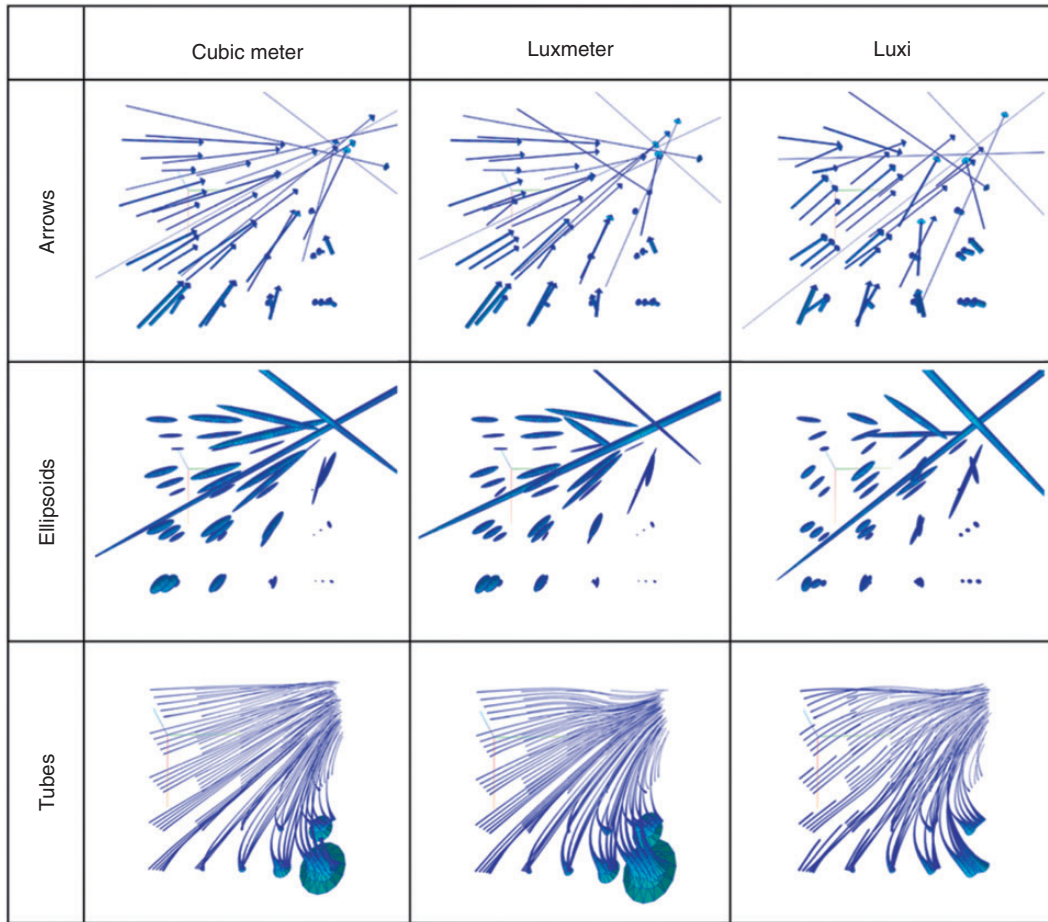


Figure 14 Measurement results, top view as in Figure 7

that by making remote measurements with the Konica Minolta device. With the handheld luxmeter and Luxi devices, the experimenter stayed in the darkest region possible and then reached out with the devices to do the measurement positions.

In addition to measurements in a real scene, our method can also be used in virtual scenes. Conducting cubic light measurements in virtual scenes requires a modelling environment that contains light measurement tools, e.g. LAA in the Autodesk 3ds Max system or calculation surfaces in DIALux.

To make measurements in a modelled scene, one should arrange the available light sensors in groups, such that in every group, six sensors would face six directions as if placed on a cube. The resulting measurements should be converted to the visualization tool input format by the user.

5. Discussion and conclusions

The main goal of the current paper was to introduce our volumetric light visualization tool and demonstrate how such visualizations

can be performed and applied to the analysis of the structure of light throughout a space. Our tool translates sets of cubic illuminance measurements into light properties values (that may be exported as a table) and visualizes them through variation of the shapes' proportions. Two main features of our tool are visualizing light volumetrically and visualizing essential light properties. The first one allows obtaining a comprehensive impression of the structure of the light field in a measured space. The second one translates the important information in easy to read visualizations. Together they provide a perception-based visualization of the 3D structure of the light flow. Visualization results are presented for two example scenes. Finally, we showed that the necessary physical measurements might be performed with light measuring tools of varying precision, all producing acceptable results.

The current implementation of our toolbox limits the visualized information to only three light properties: mean illuminance, direction and diffuseness. We chose those lower order light properties because they majorly determine the appearance of matte objects.⁵⁸ The appearance of objects made of glossy materials, such as glass and metals, is determined also by higher order light properties,⁵⁹ e.g. Kelly's⁴⁴ 'play of brilliants' or the light texture.⁶⁰ These properties cannot be extracted from our measurements because of the low angular resolution of the latter. In order to take the light texture into account, one could take a spherical photograph and use different means of processing. This light texture can safely be assumed to be rather constant throughout a scene (in the statistical sense in which it is relevant to human perception). Such a combination of our toolbox plus a statistical summary of the higher order properties of a spherical photograph would then complete such a perception-based light field analysis.

Further development of the tool implementation could include the following

features. An output of the resulting geometry would allow inserting the visualization into a model of the geometry of a scene or into a rendering of the scene. The visualization shapes are currently scaled linearly, i.e. if the mean illuminance is a hundred times bigger in one position than another, the corresponding shapes will be a hundred times bigger in size/length. The possibility of logarithmic scaling might be a suitable addition for scenes with a very high dynamic range. Finally, the interpolation methods could be more advanced in order to support the usage of irregular grids of measurement points.

The lighting design profession is using more and more digital technologies. A survey of building design professionals⁶¹ revealed that already 10 years ago 71% of the respondents used computer simulations for daylighting design. This is not surprising, these days a digital model is much cheaper and less labour-consuming to create and modify than a physical mockup. Moreover, digital simulation allows designers to perform more types of analysis and different visualizations of a design as well as quick explorations and iterations of a design. We introduced a new tool for volumetric light measurements visualization via a web interface and demonstrated how this method can be used in several light analyses and design tasks, serving a large range of applications and research in the light(ing) realm.

The need to consider the light field in its full complexity (and thus the 3D vector field instead of its two-dimensional (2D) sections) is widely acknowledged,^{15,16,23} but in practice incurs difficulties in 2D media presentations (where knowledge about mechanisms underlying visual perception in pictorial space will be helpful). We hope that the lighting community will find interest in the ideas that we have gathered in this paper and in the resulting implementation. We invite light researchers and designers for discussion, comments and suggestions about 'third

stage' approaches to lighting research and design and how to implement practical approaches to this complex problem.

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