



Sensory Evaluation of Lighting: A Methodological Pilot

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ABSTRACT

Current standards for light environments are based on technical requirements, e.g. luminance, uniformity, and illuminance, and do not necessarily describe all parts of the light experience to ensure visual comfort from a user perspective. Including experience-related requirements would most likely yield better lighting comfort. To do that, new methods for specifying and measuring the user experience are needed. This paper describes a pilot study exploring a new method to analytically assess perceived lighting properties by using a trained human panel and thus make human assessments more objective. The methodology is built on established sensory methods, where the human senses are used in product assessments, traditionally applied within e.g. the food, packaging, and car industries. An analytical panel comprising eight persons fulfilling specific selection criteria were recruited and trained to assess lighting products in a multi-sensory laboratory. The results show that the panelists were able to assess lighting by distinguishing between attributes and products. Significant differences were identified between the different luminaires, both in terms of sensory and physical properties, e.g. readability and glare. Conclusively, analytical sensory methods can be applied to lighting to assess luminaires in a non-subjective way. Physical and sensory attributes do not, however, always co-vary, which shows that data from physical and sensory measuring methods provide complementary information about light quality. This knowledge may in turn be applied in tools supporting the communication between different professions in lighting design and procurement to promote light environments that are both energy efficient and desirable from an end-user perspective.

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1. Introduction

The requirements on lighting installations are most often based on international lighting standards, such as the European standard for light environments, EN12464 (SIS 2011). These are based on photometric measures and stipulate minimum illuminance levels on the working area as well as on ceilings and walls. However, the experience created when light hits the eye is far more complex. The process cannot be fully translated into physical terms, and yet it would be needed to ensure desirable light environments.

By optimizing the luminaires and installations for these requirements, large energy savings can be obtained. In addition, advances in technology over the last decades have allowed replacement of inefficient incandescent light sources with more efficient technologies such as LEDs, incorporation of more advanced control systems, and to create new lighting concepts (Mott et al. 2012; Ul Haq et al. 2014). However, as

mentioned above, the requirements in the lighting standards were developed to ensure a minimum standard of comfort, where the occupants' working tasks can be performed without hindrance, and not to create light environments that are desirable from a user perspective. This means that energy use for lighting may be optimized without taking the experience and comfort of the user into account (Pierson et al. 2018). To improve the light comfort, user-centric measures of perceived light quality are needed.

Achieving a desirable light environment requires much more than just fulfilling minimum standards, see for instance Dutson (2010). Until now we rely simply on users' subjective experiences and the experience of manufacturers, since methods for specifying and measuring the user perception analytically, i.e. in a more objective way, are scarce. If such methods were widely used, however, the user perception could be taken systematically into account,

both in product development and lighting design and procurement.

Consumers seek products and light environments that are perceived as desirable and appealing but can usually only separate good from bad overall experiences, and seldom explain or identify the desirable properties. By sensory analysis, the perceived properties, as well as the intensity of the property, of a product can be measured. This paper focuses on analytical sensory analysis of lighting.

Over the last decades, a number of different methods and tools have been developed to measure the perception of lighting in order to complement physical lighting measurements. However, these have mainly focused on capturing *hedonic* experiences of lighting. Hedonic or affective tests are those tests that attempt to quantify the degree of liking or disliking of a product (Lawless and Heymann 2010). For example, Fridell Anter (2011) reports a method where a group of test persons, both lighting professionals and laypersons, evaluated the experience of rooms, including quality of light and colors, atmosphere, and readability. Klarén (2011) developed a tool, PERCIFAL, mainly targeting active and future lighting professionals. The tool allows systematic analysis and description of the visual experiences of a room by using well-defined and established lighting concepts. Another assessment tool was developed by Johansson et al. (2014) where laypersons evaluate the perceived outdoor lighting quality (POLQ). The evaluation is based on rating of bipolar semantic differentials, i.e. antonyms. In a similar way, Vogels (2008) developed and implemented a questionnaire aiming to quantify atmosphere perception, including lighting. A set of atmosphere terms are rated for different spatial contexts by different test groups. Other approaches combine subjective ratings of lighting with performance tasks and physical lighting properties in offices, where Knez (1995) and Knez and Enmarker (1998) capture laypersons' perception of indoor lighting by valuation of seven unipolar adjectives, while Veitch and Newsham (2000), Veitch et al. (2008) and Veitch et al. (2013) use Likert-type scales to capture office workers' satisfaction in seven lighting quality questions. Pellegrino (1999) combines semantic bipolar scales and questions to be rated on a Likert scale. Common for all the above methods and tools is that they measure the hedonic experience of lighting or light environments.

On the contrary, to predict the perception in a more analytical way, one approach in the experimental psychology is to use mathematical modeling of the perception to increase the understanding of perception from different types of stimuli. For instance, in psychophysics, the study of relationships between physical stimuli and sensory experience is of interest. Worth mentioning is the formulation of Steven's law, describing the relation between perceived sensation and intensity of the stimuli:

$$S = kI^n$$

where S is sensation intensity, I is the physical stimulus intensity, k is a proportionality constant and n is the characteristic exponent (Lawless and Heymann 2010; Wolfe et al. 2015).

In this article, we propose a sensory method for measuring the *analytical*, i.e. more objective, perception of lighting. The members of an analytical sensory panel focus on specific aspects of the assessed products as directed by scales on questionnaires. They are asked to put personal preferences and hedonic reactions aside in order to specify what attributes are present in the product and at what levels of sensory intensity, extent, amount, or duration (Lawless and Heymann 2010). Analytical sensory methods are used in other areas, such as the food and medical industries, and evaluate the human experience in an analytical, repetitive manner. The sensory measurements are taken by a trained calibrated panel and can be combined with conventional physical performance measurements to form a more complete set of data for the individual product.

Data from descriptive sensory analysis might be relevant to improve product development of luminaires, or to create user-centered requirements on lighting installations. Analytical sensory evaluation is traditionally performed in individual booths where the panelists assess the product in an isolated and standardized environment. By using this analytical method, it is possible to compare the perception of different products and to assess the different aspects of each product. The measurements need to be replicable in order to enable the assessment of different products on different occasions. The information from analytical assessments can then be connected to the consumers' subjective assessments of lighting products to

provide unique information about consumers' liking of products. In the long-term perspective, the new knowledge on which attributes govern the liking of lighting products is expected to simplify the development of new luminaires in the sense that the focus can be directed at these specific attributes. It is further expected to support communication about light quality between different stakeholders within lighting design and procurement. These facts, in turn, are expected to promote implementation of light environments that cater both energy-efficiency and user comfort.

2. Methodological background

As long as there has been a supply of goods and services, humans have judged these according to their senses. The scientific discipline of sensory analysis was defined in 1974 by Stone and Sidel (Stone 2012). Sensory analysis measures, analyzes, and interprets reactions on goods, products, and services as they are perceived by our senses: sight, smell, taste, feel, and hearing. Today, sensory methods are applied within several different industrial sectors, including in particular the food industry, medical industry, and the packaging industry. The methods are divided into *analytical* and *hedonic* methods. The analytical sensory methods are aiming toward objective measurements of perception and are performed by panelists selected to their subtle senses, while the hedonic sensory measurements include consumers and subjective opinions of the perceived sensory attributes (Lawless and Heymann 2010). Besides the mentioned industries, the methods have also been applied within the automotive industry (Giboreau et al. 2001) and to assess scents from building materials (Knudsen et al. 2007) and indoor air quality (Kolarik and Toftum 2012), but in principle, it should be possible to apply the methodology within most trades concerned with product and service development, quality control, and marketing. To the authors' knowledge, the methods are so far not used in the lighting industry.

An analytical sensory panel constitutes the measuring device for assessment of properties of a set of products. It is important to note that analytical assessments do not include any form of valuation

on whether the product is desirable or not, the attributes are measured solely according to a scale common to all panel members. The measurements are to be compared with physical measurements. The panelists are selected due to fulfillment of certain selection criteria, found among ISO-, ASTM- and CEN-standards and may therefore *not* be considered as consumers, but as analytical measuring tools (Albinsson et al. 2017). Demographic data of the panelists are therefore not required. Examples of standards for sensory analytical panel selection and sensory assessments are: ISO8586:2012, ISO13300-2:2006 and STP758. The standards describe selection and performance procedures. The selection includes lowest levels of sensitivity of the senses to be included in a sensory panel and how these levels should be tested. Further, the standards describe the procedure for how to perform analytical sensory assessments to make them valid and comparable to assessments performed in other labs.

Quantitative Descriptive Analysis (QDA) (Lawless and Heymann 2010; Stone 2012), is one of the main methods used in analytical sensory evaluation. In order to get reliable results, the recommended number of selected panelists varies between 8 and 12 persons, based upon the ability to statistically significant discriminate between products after training (Stone 2012). The low number of panelists is an advantage compared to the hedonic or consumer tests, which normally require a large number of consumers or respondents to reach statistical power (Lawless and Heymann 2010). The results of the analytical assessments are analyzed using standard statistical methods, such as analysis of variance (ANOVA) and Principal Component Analysis (PCA) (Lawless and Heymann 2010). The most common ANOVA for analytical sensory is two-way ANOVA where panelists and products are used as independent factors and the sensory attributes as dependent factors. A post hoc comparison test is normally performed to find significant differences between samples. PCA could include all resulting data and independent factors, and a PCA may be performed to give an overview of the results in order to find trends and sample outliers. Physical measurements of the lighting parameters may be conducted in parallel with sensory assessments to

provide complementary data to be used in the statistical analysis.

Since the analytical panel, together with the physical measuring instruments, is the main measuring device, it is critical to ensure its reliability. In order to obtain this, the instruments are normally calibrated against a standard. To ensure that the assessments yield analytical, robust, and useable sensory data, the panel members have to be trained and calibrated, and thereby align the evaluated attributes for all individuals included in the panel. One part of this is to keep the panelists uninformed about the technical product specifications of the test samples. However, for ethical soundness, the panelists have to be informed about the samples at an overall level. Informed consent may be needed in specific cases. Each assessment for each product is commonly measured in duplicates or triplicates in parallel with instrumental measurements.

Each attribute to be evaluated is developed and decided upon and is always defined by the panel, in collaboration with the test leader, as part of a training procedure, to ensure that the attributes are evaluated in a similar way by all panel members (Stone 2012).

2.1. Aim and research questions

The aim of this study has been to establish a method of measuring the analytical experience of lighting products and by statistical calculations connect the data with measurements of physical attributes. The study was based on the following research questions:

- Can analytical sensory analysis be applied to lighting, where panelists distinguish between products and assessments can be replicated?
- How does analytical sensory data correlate to physical data in terms of providing overlapping and complementary information about lighting products?

This paper presents the methodology and its application to lighting, as well as the results and conclusions from pilot assessments performed in 2015 and 2016.

3. Materials and method

3.1. Implementation of method

In sensory methodology, the analytical panel acts as an analytical instrument. Well-developed senses of the panel members are therefore a prerequisite for obtaining robust results from sensory assessments. Since sensory analysis is new in the area of lighting, no international standards exist. Selection criteria, which each panel member has to fulfill, therefore needed to be defined based upon criteria for other senses found in international standards, e.g. ISO 8586 (Sensory analysis – General guidance for the selection, training, and monitoring of assessors) (ISO 2012). The first and preliminary draft of criteria includes:

- Full vision on each of the eyes (after possible correction by glasses or contact lenses)
- No diagnosed eye diseases (e.g. cataract)
- Full-color vision
- Two fully functioning eyes (e.g. no squint, not over-sensitive to light etc.)

The panel was recruited based on the selection criteria. In this study, eight panelists were selected in accordance with the criteria above. The full-color vision was ensured by the Ishihara test, while the fulfillment of the other criteria was self-reported. Further, the panelists were trained to use a scale to evaluate a set of lighting attributes. The study was performed at the multi-sensory laboratory at RISE Research Institutes of Sweden in Borås, Sweden.

The first step in the sensory assessment is the training. The purpose is to train and calibrate the panel to establish a common set of attributes and to use a common scale for each attribute. It is important to mention that the panel should be seen as a measuring device, which means that personal opinions, e.g. liking of different products, should not be included at all. As with any measuring devices, calibration is essential. The initial step in the training and calibration is to define and agree on the attributes to be measured. Depending on the purpose of the sensory assessment, different types of scales may be used, for example graded scales, line scales, anchored scales etc. (Lawless and Heymann 2010).

The next step is to perform training assessments of the products in an iterative process, where at least two products with different properties are

assessed according to the established definitions. The individual assessments are compared and discussed after each round of assessment. The attribute definitions are revised when needed. The process continues until the panel has established a common scale for each attribute.

3.2. Experimental procedure

In order to validate the method, a simple 2×2 design was chosen for the products to be assessed in the pilot study, meaning that a total of four types of products were used. Table 1 shows the products and their distinguishing features.

The two varying characteristics were the correlated color temperature (CCT) and the type of optics used (white and faceted reflectors). A CCT of 3000 K provides warm white light and is typically used in the Nordic countries, and 4000 K provides neutral white light, i.e. slightly cooler light, and is the most commonly used internationally. The two types of optics are both commonly used in different downlight applications.

3.3. Experimental setting

The multi-sensory laboratory is designed according to ISO 8589:2010 (ISO 2010) and comprises 12 individual test booths. In the experimental setting, one luminaire was installed in each booth so that a total of three products of each of the four types

(Table 1) were used. The luminaires were installed in the ceiling of the booths according to the installation leaflet of the products and adjusted to give an illuminance of 500 lux on the table inside the (unfurnished) booth, according to the requirement for task lighting in the European lighting standard EN12464 (SIS (Swedish Standards Institute) 2011). The three walls of the booths were, according to the ISO standard, painted white, and the ceiling was made of white Styrofoam. To isolate the panelists during the assessments inside the booth, a white nontransparent fabric was used as a drape.





The booths were equipped with items to be viewed, as an essential part of assessing lighting is observing objects. The items included a magazine with semi-glossy paper and a color chart with four distinct colors divided into eight areas, see Fig. 1. Half the chart was covered by glass in order to view the colors with and without reflections as well as to create reflections on the table. The chart was placed in a frame with sharp edges to create distinct shades. The magazine was placed in the booths to assess readability.

The position of the chair for the observer in each booth was fixed during the experiments.

3.4. Training and calibration

The sensory analysis was preceded by four training sessions, each lasting for about 1 hour. The training included the same products as the

Table 1. Products used in the pilot study and their specific features, where CCT is the correlated color temperature.

Product number	Product name	Type of product	CCT	Reflector	Product image*
FR930	ZUMTOBEL PANOS INF E150HF 16 W LED930 LDO WH	Downlight	3000 K	Facetted specular	
FR940	ZUMTOBEL PANOS INF E150HF 16 W LED940 LDO WH	Downlight	4000 K	Facetted specular	
VR930	ZUMTOBEL PANOS INF E150HL 16 W LED930 LDO WH	Downlight	3000 K	White	
VR940	ZUMTOBEL PANOS INF E150HL 16 W LED940 LDO WH	Downlight	4000 K	White	

*www.zumtobel.com



Fig. 1. Experimental setup in the booths, where color charts with and without glazing as well as magazines were used to assess the lighting products.

experiment. To ensure that all products were covered within the same scale, the products expressing the largest difference were chosen for the training. It was of utmost importance to have a uniform definition of each attribute as well as of how to assess the attributes, for example at what point the eyes should be fixed, and where the assessor should be placed. Certain fixture points were marked in the booth ceiling. The attributes agreed upon and their definitions are shown in Table 2 and the points of observation are found in Figs. 2 and 3. Depth of color was assessed in relation to a reference color chart placed in a preparation room with fluorescent lighting (CCT 3000 K, R_A 85).

When the attributes have been set, the next step is to perform the first training assessment of the products. Each of the eight panelists assessed two products individually with the drapes closed. Before doing an assessment, each participant was asked to wait 60 seconds before starting the assessment to account for the adaptation time of the eye, i.e. let the eyes adjust to the new setting. The attributes were assessed on a line scale 0–100 anchored at 10 and 90, where 10 indicates *little* and 90 indicates *to a great extent*. The individual assessments were then collected on a board enabling all assessors to discuss and obtain consensus for the evaluations both regarding the use of the scale and how to perform the evaluations.

Based on this discussion, a careful definition of the attributes could be obtained. This was done iteratively to ensure that the assessed values coincide for all the panelists.

Disagreement on a specific attribute required a refined definition until consensus was achieved. In this way, all attributes and assessments were iterated to end up with a well-calibrated panel.

3.5. Sensory assessments

The next phase was the assessments of four types of products (Table 1) in the booths. All products were assessed in a randomized order in triplicates by all panelists. The assessments were recorded on paper for later analysis. Each assessment started at the same time, and when one assessor was ready with the particular product, he/she left the room until all assessors were finished. The adaptation time before each assessment was again 60 seconds.

The panelists were not informed about the technical product specification or the types of products to be assessed during the whole test session. The booths were labeled 1–12, and there was no other indication on the booths, so the assessors did not know which of the products they were assessing. The drapes were closed when the assessors entered the room in order to avoid seeing the light from the different booths before entering them, thus

Table 2. Attributes and definitions used in the assessment.

Place of observation	Attribute	Definition
Ceiling	Glare	Degree of glare – eye discomfort. Look from the bottom to the top of the rear wall (i.e. not directly on the light source) and look at the text that is posted on the wall in the joint between the wall and ceiling. (See a in Fig. 2.)
	Flicker	Degree of flicker (look at the text that is posted on the wall at the joint between the wall and ceiling)
	Yellowness of the light source	Degree of yellowness (look at the text that is posted on the wall at the joint between the wall and ceiling)
	Heat from the light source	Degree of heat on the back of the hand. Hold your hand at the level of the ceiling for 5 seconds.
Wall	Non-uniformity	Light non-uniformity on the entire rear wall. (See Fig. 2.) Little = completely equal distribution To a great extent = shady and non-uniform
Table top	Sharpness of shadow at the frame	The sharpness of the dominant shadow from the left side of the picture frame on the table (2–3 cm from the front edge of the picture frame) assessed at the bottom corner in level with the rear side of the picture frame. (See a in Fig. 3.)
	Sharpness of the shadow of the frame at the back edge	The sharpness and clarity of the dominant shadow from the top of the picture frame on the table, assessed near the wall where the table meets the wall. (See b in Fig. 3.)
	Multiple shadows	Degree of multiple shadows near the wall assessed where the table meets the wall. (See c in Fig. 3.) To a great extent = several well-defined shadows
	Reflection on the table	Degree of reflection on the table top in front of the picture frame with glass (near the picture frame and when varying the position of your body) (See d in Fig. 3.)
Magazine, certain page	Reflection from magazine	<i>The panelists were instructed to turn to a certain page in the magazine. Roll the magazine to half side, lift the magazine and look at the picture in the upper edge. Assess the strength/degree of reflection in the image. Assess the maximum reflection. (See e in Fig. 3.)</i>
Magazine, certain page	Readability of magazine	<i>The panelists were instructed to turn to a certain page in the magazine and read a part of the text (the body of an ad). Leave the magazine lying on the table. Assess contrast as a measure of readability.</i>
Color chart	Depth of color: Yellow	Look at the color chart in the picture frame without glass. Assess color match to the reference color in the preparation room.
	Depth of color: Blue	Look at the color chart in the picture frame without glass. Assess color match to the reference color in the preparation room.
	Depth of color: Green	Look at the color chart in the picture frame without glass. Assess color match to the reference color in the preparation room.
	Depth of color: Red	Look at the color chart in the picture frame without glass. Assess color match to the reference color in the preparation room.

minimizing the risk of preconceptions. For the same reason, the panelists were not allowed to look directly at the light source.

3.6. Physical measurements

In parallel with the sensory measurements, physical measurements of lighting attributes were conducted in the booths, including measurements of luminance, illuminance, spectra, and correlated color temperature (CCT). The luminance and illuminance were measured with a photometer (Hagner S4) and the spectra and color attributes were collected with a handheld spectral irradiance meter (Metrue SIM-2). As

for the sensory assessments, three samples of each product were measured.

The horizontal illuminance in the middle of the table was measured with and without a person in the booth. Luminance was measured of the table (looking down), of the wall (looking straight ahead), high up on the wall, of the magazine, and of the two red rectangles in the picture frame.

4. Statistical evaluation

The resulting data of the sensory and physical lighting measurements were analyzed by descriptive statistics by calculations of mean



Fig. 2. Place of observation for assessment of glare, flicker and yellowness of light source (see Table 2).

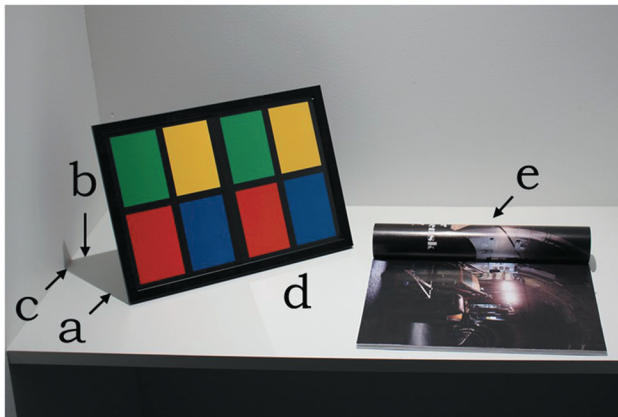


Fig. 3. Place of observation for attributes assessed on tabletop and magazine, including shadows and reflections (see Table 2).

values and standard error. Pearson correlations were performed to analyze the covariance of sensory and physical data by the use of Excel 2016, Microsoft Office. For analysis of sensory

data, analysis of variance (ANOVA) is recommended by the ISO-standards ISO 6658 (Sensory Analysis – Methodology – General Guidance) (ISO 2017) and ISO 13299 (Sensory Analysis – Methodology – General Guidance for Establishing a Sensory Profile) (ISO 2016). In this study, two-way ANOVA was performed with product and panelists as fixed factors. Bonferroni's post hoc test was applied to attributes where significant ($p \leq 0.05$) differences were found in ANOVA. Principal Component Analysis (PCA) was done to provide an overview of the results (PanelCheck V1.4.2, Nofima).

5. Results

The results from sensory assessments and physical measurements were first analyzed separately and then by Pearson correlation to investigate the covariance of physical and sensory attributes.

5.1. Sensory assessments

Sensory results (mean values) are shown in Fig. 4, while Table 3 presents the F-values and p-values for each sensory attribute. Tables 4 and 5 show differences between the sensory attributes of the products with statistical significance of 95% analyzed by ANOVA and Bonferroni's post hoc test. The results show that:

- The panelists were able to distinguish between attributes and products.
- Large and significant differences between products were found for the attributes *Multiple shadows*, *Non-uniformity*, *Glare* and *Yellowness of light source* for which the results could be associated with either CCT and/or reflector type (Fig. 4).
- The tables show that the experimental design (Table 1) has a clear impact on the resulting sensory attributes.
- Smaller, but significant differences were also found for attributes *Sharpness of shadows*, *Readability*, *Red*, *Green* and *Yellow* (depth of color). Some of the attributes could be connected to CCT and/or reflector type.

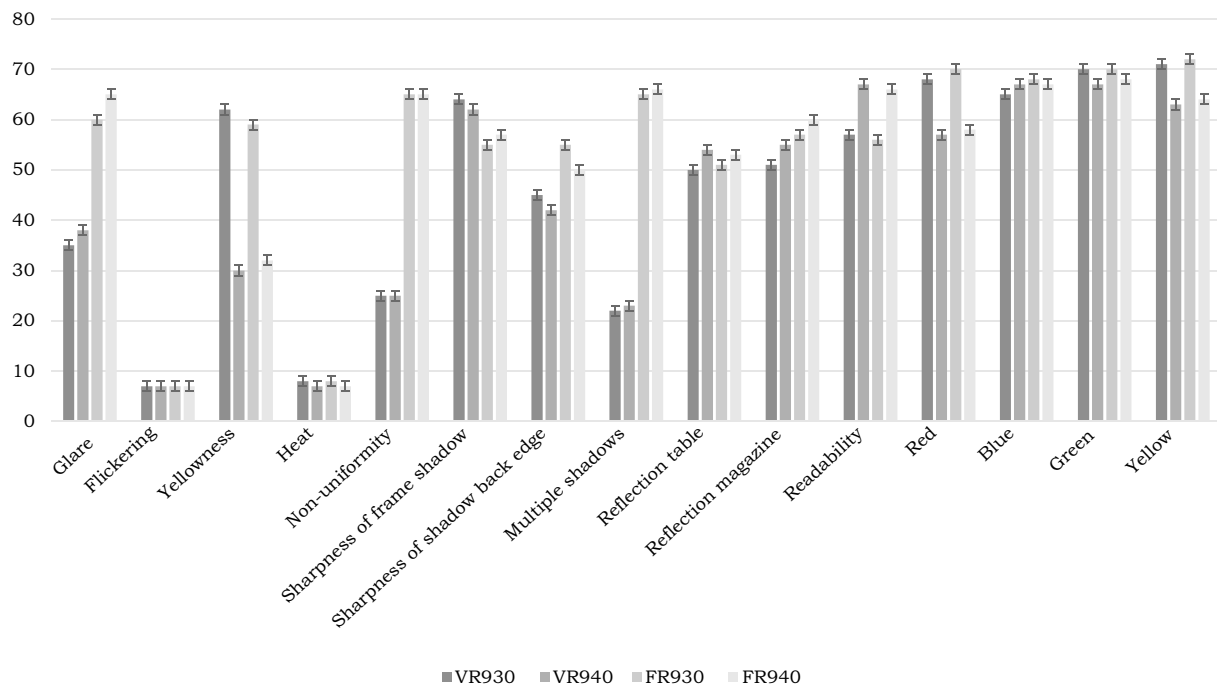


Fig. 4. Average results from the sensory assessments of the 15 attributes for the four different types of product. Error bars indicate the standard error.

- *Blue depth of color* did not differ between the products, while the other evaluated colors did.
- There is a distinct difference in shadows depending on type of reflector.
- Based on the analysis of each panelist's MSE (mean square error) and p-values, the panelists made robust assessments (i.e. low MSE and low p-value), see Fig. 5.

5.2. Physical measurements

The spectra from two of the light sources (FR930 and FR940) are shown in Fig. 6. The spectrum of

Table 3. Product F- and p-values for each sensory attribute.

Sensory Attribute	p-value	F-value
Glare	0.00	20.8
Flicker	0.79	0.35
Yellowness	0.00	38.1
Heat	0.34	1.17
Non-uniformity	0.00	105
Sharpness of frame shadow	0.01	5.32
Sharpness of shadow back edge	0.03	3.73
Multiple shadows	0.00	84.1
Reflection table	0.63	0.58
Reflection magazine	0.01	4.83
Readability	0.00	9.38
Red	0.00	12.1
Blue	0.68	0.51
Green	0.02	4.09
Yellow	0.00	5.85

Table 4. Significant differences ($p < .05$) of assessed sensory attributes associated with design parameters (optics and CCT).

Significant difference	Attribute
VR and FR (white and faceted reflector respectively) differ significantly in the following attributes	<ul style="list-style-type: none"> • Glare • Non-uniformity • Multiple shadows
930 and 940 (Correlated Color Temperature, CCT, of 3000 K and 4000 K respectively) differ significantly in the following attributes	<ul style="list-style-type: none"> • Yellowness of light source • Readability • Depth of color red, green, yellow
No significant differences were obtained in the following attributes	<ul style="list-style-type: none"> • Flickering • Heat • Reflection table • Depth of color blue

Table 5. Other significant differences ($p < .05$) of assessed sensory attributes with no obvious association with design parameters.

Significant differences	Attribute
VR930 differ significantly from FR930 and FR940, while FR930 also differ significantly from VR940	Sharpness of frame shadow
FR930 and FR940 differ significantly	Sharpness of shadow back edge
VR930 and FR940 differ significantly	Reflection magazine

the warmer light source (FR930, 3000 K) has a larger contribution of red light shown by the higher peak around 620 nm.

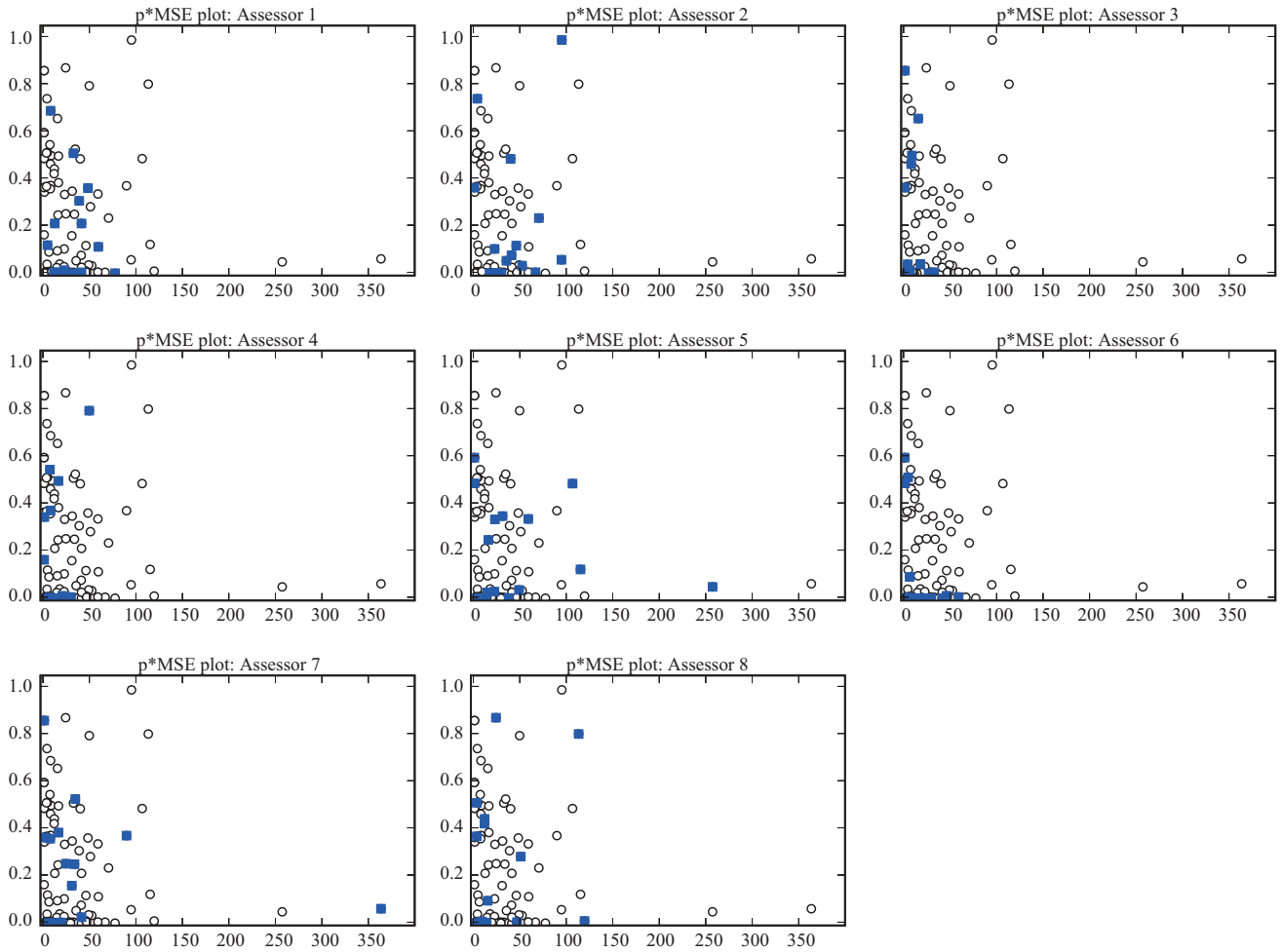


Fig. 5. The mean square error (MSE) and p -value of each of the eight panelists, showing each assessor's ability to replicate assessments and to distinguish between samples, respectively.

Further results from the physical measurements, i.e. luminance measurements on the experimental objects, are found in Fig. 7 as well as in Tables 6 and 7. The mean values for the illuminance with a person in the booth varied between 409 and 415 lux for the four different luminaires. The physical measurements showed significant differences related to CCT and reflector type.

The luminance in the booths is higher with the diffuse reflector except for the luminance of the table. This is because the luminaires were set to give an illuminance of 500 lux on the table directly below the light source in the unfurnished booth. Consequently, the LEDs with diffuse reflectors (VR930, VR940), where light is reflected and reaches all parts of the booth, need to have a higher total luminous flux than the LEDs with the faceted reflectors (FR930, FR940)

that provide directed downward light. Thus, the illuminances on the walls and ceiling are higher with the diffuse VR-reflectors.

The spectra and the CCT values show differences between the warm white light (VR930, FR930) and the more neutral white light (VR940, FR940), as expected. Although the differences are too small to be significant, the luminance from the red-colored rectangle in the picture frame is higher with the warm white light, which is reasonable since the spectrum of the warm white light has a higher contribution of red light.

No differences were found in luminance values measured on the magazine for the four types of products. *Luminance magazine* was therefore not included in the correlation analysis between physical and sensory data.

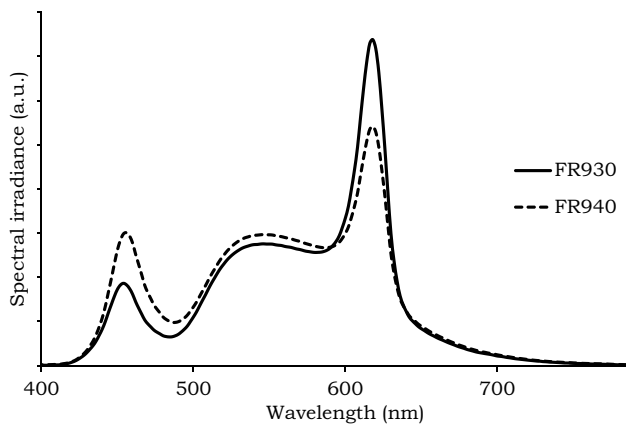


Fig. 6. The spectral irradiance from two of the light sources with different correlated color temperature (CCT). The curves are weighted to the respective luminance.

5.3. Pearson correlations

Pearson correlations were made to evaluate the degree of covariance between physical and sensory measurements, see Table 8. Correlation coefficients at 0.9 or higher were noted. The following covariance between sensory and physical attributes can be observed in Table 8:

- *Glare* is negatively correlated to the *luminance at the joint between wall and ceiling*. The setting with the faceted light source was assessed as giving more discomfort (glare) when looking at a spot beside the actual light source. The luminance of this spot was lower than with the diffuse reflector, however the contrast was higher.

Table 6. Significant differences ($p < .05$) of measured physical attributes associated with design parameters (optics and CCT).

Significant difference	Attribute
VR and FR (white and faceted reflector respectively) differ significantly in the following attributes	<ul style="list-style-type: none"> • Luminance Wall straight ahead • Luminance Joint between wall and ceiling
930 and 940 (Correlated Color Temperature, CCT, of 3000 K and 4000 K respectively) differ significantly in the following attributes	<ul style="list-style-type: none"> • CCT
No significant differences were obtained in the following attributes	<ul style="list-style-type: none"> • Illuminance of table, person in booth • Luminance Magazine • Luminance Table

Table 7. Other significant differences ($p < .05$) of measured physical attributes with no obvious association with design parameters.

Significant differences	Attribute
VR930 significantly differ from FR940	Luminance Red without glass

- *Yellowness of the light source* is highly correlated to the *Luminance red without glass* and negatively correlated to *CCT*. Light sources with lower correlated color temperature (CCT) generate warm-white light, i.e. yellow-like, and thereby a sense of higher degree of yellowness of the light source. Additionally, as can be seen in Fig. 7, the *luminance red without glass* is slightly higher for the two fixtures (VR930 and FR930) with lower

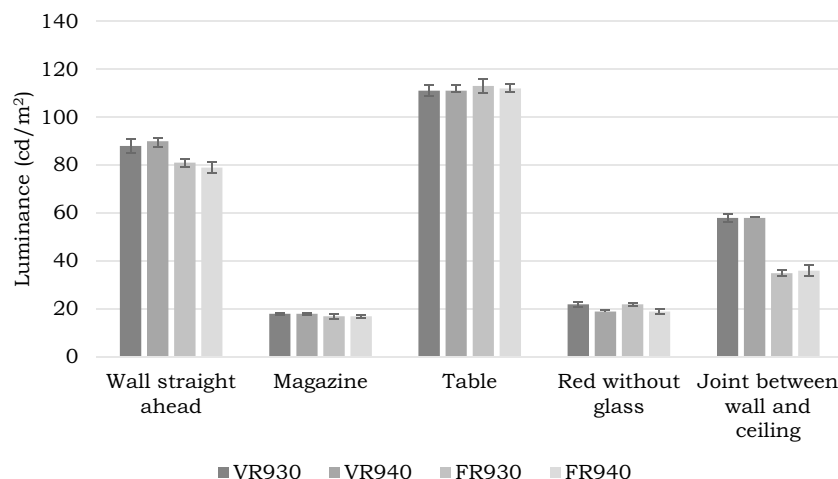


Fig. 7. Average results and standard error from luminance measurements on the four types of products.

Table 8. Pearson correlations showing the covariance between sensory assessments and physical measurements. The table only shows high correlations, with correlation coefficients ≥ 0.9 .

Physical Measurement	Sensory Assessment
Luminance Straight ahead	Glare (−0.97) Non-uniformity (−0.98) Sharpness of frame shadow (0.92) Multiple shadows (−0.98)
Luminance table	Non-uniformity (0.90) Sharpness of shadow back edge (0.99)
Luminance red without glass	Yellowness (1.00) Reflection table (−0.96) Readability (−1.00) Depth of color: Red (1.00) Depth of color: Green (0.96) Depth of color: Yellow (1.00)
Luminance Joint between wall and ceiling	Glare (−0.99) Non-uniformity (−1.00) Sharpness of frame shadow (0.98) Sharpness of shadow back edge (−0.91) Multiple shadows (−1.00) Yellowness (−0.99)
CCT	Reflection table (0.95) Readability (0.99) Depth of color: Red (−0.99) Depth of color: Green (−0.92) Depth of color: Yellow (−0.99)

CCT, since warm-white light has a higher contribution of red light.

- *Non-uniformity* and *shadows* are correlated to *Luminance* values, as they are both associated with the non-uniform light distribution in the booths, which is due to the faceted reflectors.
- *Sharpness of shadow back edge* is highly correlated to *Luminance of table* as a consequence of the light distribution from the faceted reflector. However, the differences in table luminance between the different settings are very small (see Table 6 and Fig. 7) and therefore the correlation might be a statistical artifact.
- *Multiple shadows* are negatively correlated to *Luminance straight ahead* and *Luminance joint between wall and ceiling*. The correlation originates from the type of reflector. Light diffusion from the white reflector results in higher luminance on the walls and more uniform light distribution, which in turn produces few multiple shadows.
- *Sharpness of frame shadow* is correlated to the *Luminance straight ahead* and *Luminance joint between wall and ceiling*. The correlation originates from the type of

reflector. Due to the absence of multiple shadows, the frame shadow is perceived sharper.

- The correlation between *Reflection on table* and *CCT* is high in Table 8. However, there is no significant difference in *Reflection on table* between the luminaires with different color temperature, see Table 3 and 4. The *Luminance red without glass* is negatively correlated to CCT due to the higher contribution of red light in warm-white light, which in turn results in negative correlation to *Reflection on table*.
- *Readability* and *CCT* are highly correlated; the panelists assessed that the readability was higher in the neutral white light. The negative correlation with *Luminance red without glass* is again due to the higher contribution of red light in warm-white light (lower CCT).
- *Depth of colors*, except for blue, is highly correlated to *Luminance red without glass* and *CCT*. Thus, red, yellow, and green colors appear with a higher degree of color depth in the warm white light compared to the neutral white light due to the difference in color spectra.

5.4. Principal component analysis (PCA)

Fig. 8 shows a PCA (Principal Component Analysis) plot of the mean values for the four included samples, showing 99.9% of the variance in the resulting data. The four samples are well spread in each of the four quadrants. Along the first principal component, showing 77.6% of the variance, samples VR (white reflectors) are in one end and FR (faceted reflectors) are in the other. The FR samples are plotted in the same direction as the attributes *Multiple shadows* and *Non-uniformity*, the VR-samples can be considered as opposite and by that being more uniform. Along the second principal component, showing 22.2% of the variance, the correlated color temperature (CCT) is reflected; samples with CCT 3000 K are yellow while the 4000 K-samples are opposite and thereby not yellow. The results altogether show that the design had a clear impact on the assessed attributes.

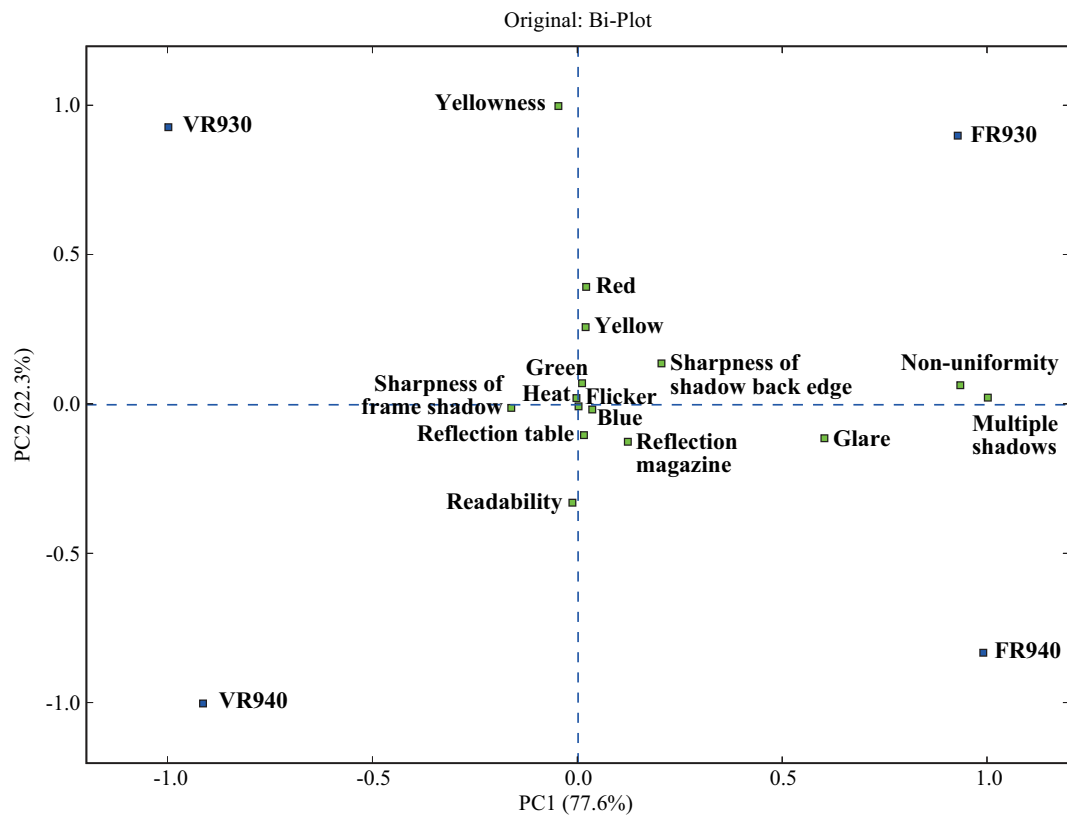


Fig. 8. PCA plot of samples and measured sensory attributes.

6. Discussion

This paper describes a new method for analytical assessment of lighting as well as results from pilot assessments in a laboratory setting. To include variations associated with production, three products of each type were used in the study, which is considered as triplicates. This approach follows recommendations in sensory literature to ensure robustness of the results (Lawless and Heymann 2010). As was shown in the result section, the test design (correlated color temperature, CCT, and optics in terms of reflector) was useful in terms of providing data that could be related to the included design properties in order to develop the sensory methodology. Moreover, the adaptation period of 60 seconds should be validated by future studies. Eye adaptation periods from 1 min (Nakamura and Obinata 2017) up to 10 (Sullivan and Donn 2017) and 20 minutes (Tiller and Veitch 1995) are reported in literature. In this study, a small pretest was performed and discussed among the panelists and other experts prior to the decision of a 60 second adaptation period.

In line with previous studies, we have identified attributes that need to be explored further, including glare, colors, readability, and shadows:

- The perception of glare was not straightforward, which has also been shown in previous studies (e.g. Clear 2012; Pierson et al. 2018). In the first training session, some of the panelists considered the faceted reflector setting with more directed downward light to produce more glare, while the other panelists evaluated the diffuse setting (with a higher luminance of the joint between wall and ceiling, i.e. the point of observation) to produce more glare. During training, however, a refined definition of glare was established, enabling all panelists to make comparable assessments. The assessments negatively co-vary with physical measurements of luminance, meaning that the perception of glare does not necessarily increase with luminance but rather with contrast. In line with Pierson et al. (2018) it can be seen that luminance had an influence on glare.

- The appearance of colors was assessed with a reference in a room with fluorescent lighting with a correlated color temperature (CCT) of 3000 K. One might speculate that the result could have been different with a reference in daylight and, as suggested by Royer et al. (2018), the color perception varies with CCT and chromaticity. However, a reference was used to provide the panel with a common reference point on the assessing scale for a specific attribute. The point could be placed wherever on the scale. Perception and definitions of color are not trivial and have been extensively explored in previous research (e.g. Szybinska Matusiak and Fridell Anter 2013). Sensory assessments of color need to be further investigated, for instance based on the needs of the lighting industry and professional customers, for example by providing information that complements the color rendering index.
- The readability is highly correlated to the CCT of the light. Colder color temperature was experienced to produce higher contrast and thereby higher readability. This is in line with the studies reported in Navvab (2001) and Berman et al. (2006), where higher CCT at the same luminance yielded better visual acuity for young adults and school children, respectively.
- Shadowing is of great importance in lighting design (Fridell Anter 2014). In the pilot tests three different attributes were assessed to describe the shadows; Sharpness of frame shadow, Sharpness shadow back edge, and Multiple shadows. As expected, the faceted reflectors clearly produced multiple shadows of the picture frame, since it provides more direct light compared to the diffuse reflector, which reflects light in all directions. This can be compared to Dutson (2010) who argues that flat diffused light is without volume or structure. To provide a more comprehensive picture of how shading is experienced, the shadow-related sensory attributes should be refined and further extended, for instance by including the direction of the shadow.

A light environment consists of many sources of light, such as different luminaires, windows, mirrors etc. Results from sensory assessments of lighting products in laboratory settings should, therefore, be applicable in real contexts with natural distractions, i.e. where lighting products will appear in practice. This type of sensory testing has been done in the area of food, where for example wine has been tested in combination with cheese (Nygren 2004; Nygren et al. 2017). The outcome from analytical assessments in the laboratory and in real context should coincide, which would verify the methodology further. Still, results from laboratory assessments provide valuable information on perceived lighting attributes and how they vary between different products. Analysis of sensory data in relation to physical measurements further provides insights on what perceived lighting characteristics co-vary with physical properties and what are the major differences between measured and experienced lighting.

Most previous methods and tools measure hedonic user perception of lighting, i.e. tests that attempt to quantify the degree of liking or disliking of products (Lawless and Heymann 2010). The proposed method builds on *analytical* assessments by a trained panel, i.e. tests where personal preferences and hedonic reactions are set aside in order to specify what attributes are present in the product and at what levels of sensory intensity, extent, amount, or duration (Lawless and Heymann 2010).

The results from the pilot tests show that lighting can be assessed analytically and yield non-subjective insights on perceived light quality. This data can be correlated to consumer preference data (i.e. data from consumer surveys), since consumers can usually only separate good from bad products, but seldom identify or describe what properties are perceived as good or bad. Experiences from other areas of application, such as the food industry, have shown that data from analytical sensory assessments can successfully be combined with consumer data in so-called preference mapping (see e.g. Cadena et al. 2012). It is a powerful statistical tool to be used in product development, since it rapidly points out different preferences among consumer groups and relate these to physical and analytical sensory attributes (MacFie 2007). Thus, this allows the consumer to achieve the desirable lighting properties that are sought after.

Analytical sensory assessments are intended to complement physical measurements and to provide added value, not to replace them. As has been shown in this paper, analytically evaluated lighting attributes can provide complementary information about lighting products and light environments that cannot always be captured by physical measurements, for instance readability and depth of color. This knowledge can support user-driven development of energy-efficient lighting within the lighting industry, as well as promoting user-centered requirements on light environments on the customer side.

7. Conclusions

A method to analytically measure the experience of lighting products by a trained analytical sensory panel has been established in a pilot study and data from the assessments have been connected with physical measurements by statistical calculations. Significant differences between the different luminaires were identified, both in terms of sensory attributes and physical attributes. This research project constitutes a first step to utilize sensory methodology in new areas of application. The outcome indicates that sensory methods can be applied to lighting to analytically assess luminaires in a non-subjective way. More studies are, however, required to validate the methods. It should be noted that the physical measurements and sensory results do not always covary. It can, therefore, be concluded that a concept of light quality needs to take both physical and perceived properties of lighting into account.

8. Future work and limitations

The work presented in this paper can be regarded a pilot study and thereby a number of limitations may be mentioned. One possible improvement is revision of the criteria for panel selection in order to reach more reliable results. For instance, the light sensitivity and age of the panel members may need to be taken into account, while eyesight correction with glasses may affect the perception of glare and should perhaps be excluded. Furthermore, the performance procedure including trainings and assessments should be further validated. Especially, the complexity of light has to be taken into account and thereby also the objects chosen to assess lighting attributes. In this

study, the white surfaces of the booths were designed based on international standards, while chromatic colors and objects were chosen based on pre-studies and discussions with lighting experts, both researchers and practitioners. Since materials and textures have a significant impact on the light experience, the objects to be viewed during assessment may be reconsidered or supplemented to include different structures and shapes, and thereby allow further examination of the perception of shadows.

Assessments of color are particularly complex but were still included in the pilot study in order to cover a variety of perceived lighting attributes and thereby enable identification of covariations between different attributes of light sources. Still, more work has to be done in order to perform reliable sensory assessments of different colors.

Moreover, further development of methods for analytical sensory lighting assessments in particular consists of two parts; assessment in real contexts and to make the method available to different stakeholders by developing tools for light quality communication.

Assessments in real contexts, i.e. outside the laboratory setting, where the product is introduced in an environment with natural distractions, aim to verify the applicability of the method. In case the analytical assessments in a real context generate equivalent results to laboratory assessments, it verifies that the generated knowledge on perceived lighting attributes is valid not only in laboratory settings, but also in real applications (e.g. office environments). It will further provide the possibility to assess properties of large or complex lighting fixtures that cannot be fit into the test booths.

Sensory lighting assessments possess a considerable potential to support the existing description of light quality and comfort, which is based on physical lighting properties. Therefore, methods and tools to evaluate and communicate quality of light will be developed based on perceived and analytical sensory measurements. The aim is to support communication between different professions in lighting design and procurement, and to support light environments that cater both energy efficiency and well-being. The engagement of the lighting industry and practitioners in such development is crucial to ensure applicability of the outcome.

Lastly, results from analytical sensory assessments and physical measurements may be connected to consumer preference studies by statistical methods. Lighting attributes, both sensory and physical, governing the liking of luminaires and light environment can thereby be identified, which supports the lighting industry to focus on specific attributes.

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