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User-Centric Measures of the Perceived Light Qualities of Lighting Products

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Abstract

Nowadays, lighting planning is predominantly determined by the need to meet physically measurable requirements that are often based on current lighting standards. However, meeting the minimum technical requirements of the standards is no guarantee for a visually appealing light environment. Instead, requirements based on perceived light qualities also need to be included to achieve better user comfort. Taking perception-based qualities into consideration when creating a light environment is, for many, not an easy task. In addition, a common terminology for perceived light qualities is currently lacking, both in industry and in research. The aim of this paper is, therefore, to explore how perceived light qualities of white light sources can be described when employing user-centric measures. The focus was on the qualities of light colour and diffuse and distinct light since these qualities have a great impact on the visual impression of light. The perception was assessed by applying analytical sensory analysis to lighting products, a method found to be promising in previous work. The methodology is based on analytical measurement by the human senses, which is particularly valuable when developing a general terminology. Since sensory analysis is still quite new to the topic of lighting, the applicability of using the methodology to assess lighting in a real context was also investigated. The results of the studies showed that the perception of light qualities can be described using further concepts in addition to those currently used. For light colour, the concepts of reddish, bluish, yellowish, and greenish light colours proved suitable for providing a richer description of the quality. The concepts of diffuse and distinct light satisfactorily captured variations in light contrast produced by shadows, reflections, and sparkles. In addition, the studies revealed that analytical sensory analysis was applicable for assessing the perception of lighting in a real-world context. The latter means that knowledge gained in the laboratory can be translated into real environments. The user-centric measures investigated in this paper have contributed to the terminology related to perceived light qualities. These can complement the physical measures in lighting planning to promote light environments that are not only energy efficient and meet technical requirements, but also cater for increased user comfort.

Keywords:

Visual Perception;
Lighting Assessment;
Sensory Analysis;
Light Qualities;
Light Colour;
Diffuse Light;
Distinct Light;
Analytical Assessment.

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1- Introduction

The design of indoor environments is important for people's comfort, well-being, and, in the long run, health [1–3]. The qualities and design of the lighting contribute significantly to the overall room experience [4, 5] and are dependent on the properties and performance of the light sources. The visual qualities of light sources are largely described using technical and physical parameters; however, these provide only very limited insight into the perceived qualities of the

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light. Two light sources with similar physical performances can, for example, create different experiences depending on how the light is distributed [6]. Conversely, two light sources produced using different technologies may give a similar visual experience. Thus, physical measures do not sufficiently describe and cannot be directly linked to the perceived qualities of a light source; this means that physical measures need to be complemented with measures of perceived quality. However, common terminology and reference systems for describing perceived light qualities are lacking in both the lighting industry and research, not least for LED lighting [7]. During procurement, for example, architects and interior designers often find it difficult to motivate the perceptual and aesthetic values of lighting. Moreover, the recent technological development of energy-efficient light sources due to the EU Directive on Ecodesign [8] has created opportunities for different lighting solutions and greater variation in light qualities and technical performance. In addition, the standardized measures are difficult to apply to LED technologies [9–12]. Together, these factors complicate comparisons or quality assessments of the lighting products when considering perception-based qualities. Choosing the best light source for the purpose—and ultimately designing good light environments—has become more difficult for both private consumers and professional actors. In order to promote light environments that cater for user comfort as well as meet technical requirements and promote energy efficiency, this paper will explore user-centric measures of the perceived light qualities of lighting products.

In many industries, perceived qualities are a natural part of product development as well as product information and marketing. There are several methods for measuring and analysing such qualities. One method is sensory analysis, which has been successfully used in various commercial and academic areas for many decades [13]. However, it has not been commonly used for evaluating light qualities, although it has been shown in previous work to be a promising method [14, 15]. Analytical measurement by the human senses has been employed in this paper since this methodology is particularly useful when developing a general, non-subjective terminology.

1-1- Background

In order to provide a background to the sub-studies in this paper, a description of how existing lighting standards and guidance relate to perceived light qualities is presented and complemented by experiences from current lighting planning. Examples are given of physical measures relevant to the sub-studies together with the perceived light qualities. The method for measuring perceived light qualities is then described.

1-1-1- How Lighting Standards and Guidance Relate to Perceived Light Qualities

There are a number of different norms and regulations to be complied with in lighting planning, such as international lighting standards and regulations from various authorities. The European lighting Standard EN 12464-1:2021 *Light and lighting - Lighting of work places - Part 1: Indoor work places* [16] was developed to ensure a minimum level of visual comfort. This is mainly based on physical measurements and measuring systems, and defines specific requirements and recommendations for task areas and surrounding areas in office, educational and healthcare environments, and other public or commercial premises. Compared to previous versions, the 2021 version of the standard addresses users' needs to a greater extent, for example by highlighting the need for differentiated and adjustable lighting conditions. However, achieving a desirable light environment requires much more than just fulfiling minimum requirements and, although the standards were created with good intentions, it is possible, and even common, that light environments offer neither good visual qualities nor an appealing atmosphere [2, 6]. The norms and recommendations for illuminance levels, as well as common practice, may be questioned since in many cases they exceed what is necessary for effective visibility. For instance, studies show that increased illuminance does not necessarily lead to better visual performance and well-being in work places [17]. In addition, research studies indicate that preferences for light level are individual and may be well below the recommended levels for illuminance for lighting in work and general environments. Several of these studies also show that contrasts and light distribution have a greater impact on perceived light level and experience in the room than illuminance levels [18-20]. These findings indicate that there may be strong advantages in considering perceived light qualities to a greater extent. This could lead to optimising light environments, luminaires and light sources with regard to design, use, technical requirements and electricity consumption (through decreasing excessive illumination).

However, well-defined quality requirements, in addition to the quantifiable requirements in the standards, are not common when planning and procuring lighting in properties. There are also challenges related to highlighting the non-technical values of a building project since they are not easily measured or evaluated. Architects and interior designers often find it difficult to motivate perceptual and aesthetic values in relation to financial and technical requirements. In addition, the terminology describing light as a visual phenomenon is underdeveloped, and the existing recommendations and guidelines give little information about how requirements that are not expressed in numbers should be formulated, realized and evaluated. This is particularly challenging for those lacking expertise in lighting design – typically builders, clients, electrical consultants etc. [21-23].

Nevertheless, to facilitate the work of lighting planning, there are some guidelines where perceived qualities are addressed to some extent; for example, the international certification system WELL [24]. This system aims to raise the quality of buildings in terms of how to better meet the users' needs and well-being, which includes the light environment. In several countries, there are also examples of documents and guidelines that provide information about the visual and perceived qualities of light [25, 26]. However, since these do not provide measuring systems or established definitions that can be referred to in construction documents and specifications, they primarily reach lighting professionals and not clients, electrical consultants, or private consumers. By exploring user-centric measures, the intention in this paper is to contribute to finding and testing concepts and definitions of perceived light qualities that can provide guidance when choosing suitable lighting products.

1-1-2- Physical and Visually Perceived Measures of Light Qualities

The physical measures commonly used to describe the qualities of light sources and light environments are the various photometric measures that are correlated to the spectral and light sensitivity of the human eye. For instance, photometric measures specify the light emitted from a light source, expressed as the luminous flux or the incident flux on a surface (illuminance). Another measure is the colour rendering index, which specifies the ability of a light source to faithfully reveal the colours of objects. The colour appearance (chromaticity) of a white light source is indicated using the measure of colour temperature, which corresponds to the temperature of an ideal blackbody that emits light in a colour tone comparable to the light source. For light sources such as fluorescent lamps and LEDs that are not based on incandescent light technology and therefore cannot be approximated by a blackbody, the measure of correlated colour temperature is used.

While colour temperature can be physically measured, perceived *light colour* is what the human eye can observe, and there is no exact connection between these measures. Two light sources with the same correlated colour temperature can appear to be different with regard to light colour [27, 28]. This may be due to physically measurable deviations from the light distribution from an ideal blackbody [29, 30], to human perception [31, 32], or to human eyesight being very sensitive to these colour differences [28, 33], as is known from colour research [34, 35]. Perception in general [36], and not least colour vision [37], is also context-dependent and is affected variously by the different properties of light sources, such as colour temperature and colour rendering [38–40]. There are, however, no (precise) measures to describe perceived differences in light colour. Experience shows that the well-established concepts of warm, neutral, and cool light colour, as commonly used in the industry, are often too general to be completely useful in describing perceived light colour [41]. New concepts to better describe this aspect were therefore introduced and evaluated in the studies in this paper. These concepts were reddish light colour, bluish light colour, yellowish light colour, and greenish light colour, which were chosen based on the outcomes of workshops with lighting experts/practitioners.

The character of light can be further described on the basis of two fundamental and interacting factors: light level and contrasts. Contrasts between lighter and darker areas can be achieved through a light distribution that makes shadows, highlights, and reflections/sparkles in different materials. The distribution of light has a great impact on how a room is experienced visually and on its atmosphere. Lighting that creates soft contrasts between shadows and highlights, and provides a varied light, often makes the light environment more pleasant [6]. Creating this varied light has been described by Kelly [42] using a stepwise lighting design and adding different types of lighting to create focused light, ambient light, and accentuated light with shadows, highlights, and reflections. The opposite of varied light is lighting that provides an even and shadow-free light without much variation. The design and physical properties of light sources and luminaires also affect how light is distributed in a room. An omnidirectional and frosted light source, for example, distributes light in a different way from a spotlight.

So, what concepts could be used to describe the qualities of these different lighting principles with and without light contrasts? When the light distribution is even, the light can be described as diffuse and lacking contrast. The lighting industry often talks about direct or directed light when the light has a clear direction from a light source, creating shadows. However, direct and directed describe the type of light distribution rather than the actual quality of the light created. This paper, therefore, explores whether the concepts of *diffuse* and *distinct* light could serve as opposites to express these light qualities. These concepts were chosen as a result of workshops held with lighting experts and practitioners.

1-1-3- Measuring Perceived Light Qualities

Over the past decades, a number of methods and tools have been developed to measure the perception of lighting as a complement to physical lighting measurements. For example, a method to evaluate perceived outdoor lighting quality

(POLQ) was developed [43], while other approaches combine subjective ratings of lighting with performance tasks and physical lighting properties in offices [3, 44-48]. Others present methodological recommendations for evaluating subjective perceptions of different light qualities, such as perceived colour rendition [49]. The common feature of all these methods and tools is that they measure the hedonic that is the subjective, experience of lighting.

The purpose of this paper is to develop descriptive, non-subjective concepts for light qualities where personal preferences and hedonic responses are not considered. Since 2014, analytical sensory methodology has been developed to assess light sources and luminaires and describe and quantify perceived light qualities in a non-subjective way [14]. The scientific discipline of sensory analysis was first defined in 1974 by Stone [50]. It measures, analyses, and interprets people's reactions to goods, products, and services as perceived by the human senses: sight, smell, taste, feel, and hearing. Analytical sensory methods aim at obtaining objective measurements of perception and are performed by panellists who are selected for their well-developed subtle senses, while hedonic sensory measurements are made by consumers giving their subjective opinions [51]. By statistically analysing data from analytical sensory assessments, physical measurements, and consumer tests, parameters that govern the liking of products can be identified.

Sensory methods can be applied within most trades concerned with product and service development, quality control, and marketing. In particular, sensory analysis is used in the food, medical, and packaging industries. It has been further applied within the automotive industry [52] and to assess odours from building materials [53] and indoor air quality [54]. Sensory analysis of lighting products is new, and the methodology and procedure for the analytical sensory assessment of lighting are described in detail in Boork et al. [15]. The authors note that although sensory methodology can be applied to the perception of lighting, further studies are required in order to verify the applicability of its use in real environments. Since lighting products can normally be found in environments that are more varied than laboratories, the current paper investigates whether equivalent results can be obtained in a real context. If so, this would imply that the applicability of the method has been strengthened.

The studies in this paper are conducted in a Swedish context. It has long been known that preferences for how we light our homes and other indoor environments vary between countries and cultures [55, 56]. Since the approach used in the current studies has less to do with people's preferences for a certain lighting and instead focuses on analytical (objective) descriptions of how panellists characterise light from different light sources, the differences between countries should be of less importance. This paper contributes to the ongoing research on the perception of the visual qualities of lighting and related areas (e.g. [27, 49, 57]). In addition, it responds to the need in the lighting and real estate industries for an established terminology to describe perceived light qualities. This could then be used in lighting planning to promote light environments that are not only energy efficient and meet technical requirements in lighting standards, but also cater for user comfort. An exploratory approach is applied using analytical sensory analysis – an approach new to both lighting research and industry. The focus is on *sensory* experiences of light qualities from *light sources.* The studies use commonly available consumer products with white light sources so that the knowledge acquired can be applied in guidance for both professionals and consumers.

2- Objective and Research Questions

The main objective of this paper is to explore user-centric measures of the perceived light qualities of lighting products using sensory analysis. The measures in focus relate to the light qualities *light colour* and *diffuse and distinct* light from white LEDs. The applicability of using analytical sensory analysis in real contexts is also investigated.

The following research questions are addressed:

1. *How can the perception of light colour and of diffuse and distinct light be described? (**RQ1**)*
2. *How do different product properties influence the perception of light colour and of diffuse and distinct light? (**RQ2**)*
3. *Can analytical sensory analysis of lighting be performed in real contexts? (**RQ3**)*

3- Research Methodology

User-centric measures of perceived light qualities were explored in three different sub-studies conducted in 2016, 2017 and 2018, respectively. The following sections describe the experimental designs and settings of the sub-studies and how the sensory assessments were carried out. The overall research methodology is illustrated in Figure 1. For details of the methodology for the sensory evaluation of lighting, see Boork et al. [15].

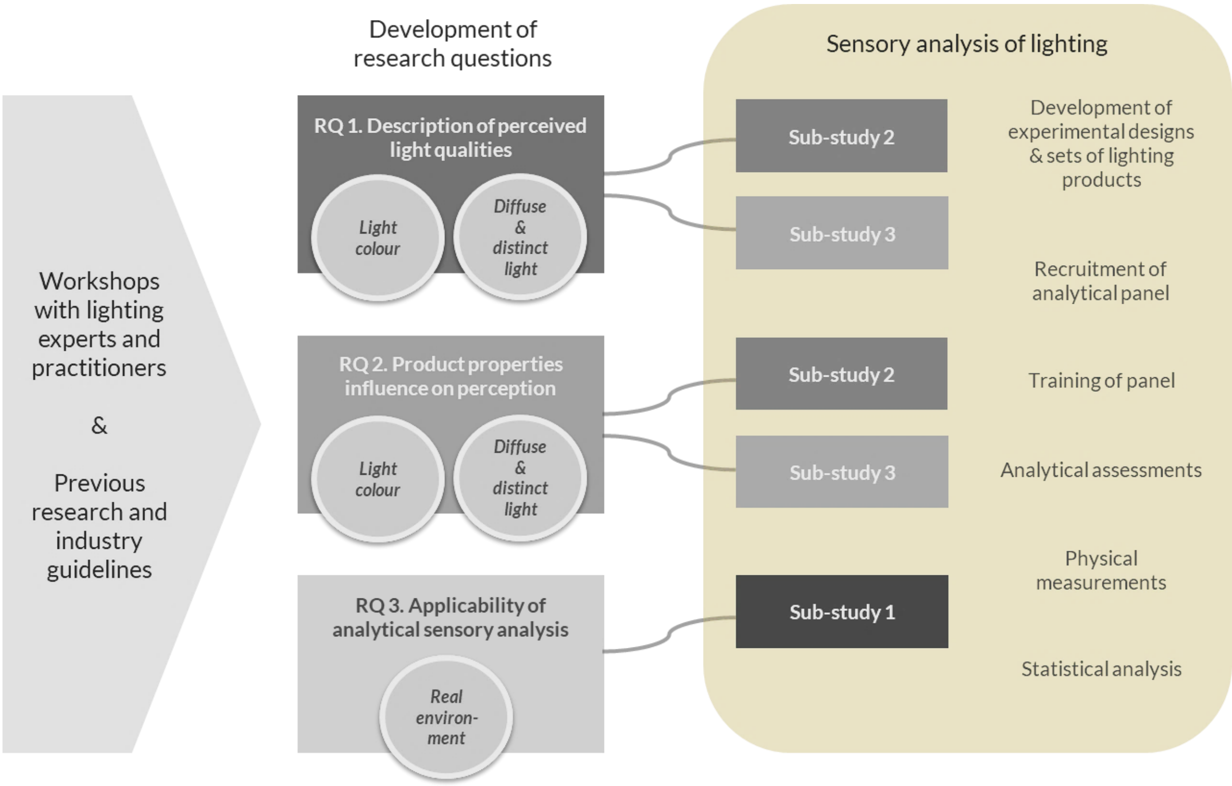

Figure 1. Flowchart of the research methodology

3-1- Sensory Assessment of Lighting

Analytical sensory methods have been applied to lighting products in order to assess the perceived qualities of light sources in a non-subjective way. In sensory analysis, a trained panel assesses a set of qualities analytically, that is, without taking personal preferences or opinions into account. The panel therefore functions as a physical measuring device. Panellists with well-developed senses are thereby a prerequisite for obtaining robust and usable sensory data [13]. In areas where sensory analysis is well established, the selection of panel members is regulated by international standards. However, since sensory analysis of lighting products is new, no such standards exist. Instead, the selection criteria from [15] were used:

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

Each panel member had to fulfil all the criteria to be included. Full-colour vision was ensured using the Ishihara test, while fulfilment of the other criteria was self-reported. In total, eight panellists were recruited for the 2016 and 2018 tests and seven for the 2017 test.

3-2- Experimental Designs

The experimental design and sets of lighting products were adapted to the focus of each sub-study in the following ways:

- *Sub-study 1* (2016) aimed at verifying the applicability of using the methodology by applying the same experimental set-up in the laboratory and in a real context, respectively (RQ3). The experimental design comprised four recessed spotlights and was chosen due to the prerequisites associated with the real context (offices in a research villa; see Section 3-3). The products used in the sub-study were varied according to the following design factors: correlated colour temperature, CCT (2700, 3000, and 4000 K), luminous flux (340–600 lm), type of light emitting technique (new/old).
- *Sub-study 2* (2017) aimed at exploring light colour and diffuse/distinct light (RQ1 and RQ2). The experimental set-up included the following design factors: clear and frosted light sources, correlated colour temperature, CCT (2700 and 4000 K), and light distribution angle (directed and omnidirectional light sources), while keeping the luminous flux at about 250 lm.

- *Sub-study 3* (2018) deepened the assessment of light colour and diffuse/distinct further (RQ1 and RQ2). This included, for instance, the design factors: luminous flux (250-470 lm) to explore the effects on the perception of diffuse and distinct light, and colour rendering index, CIE R_a/CRI (≥ 80 and ≥ 90) to find out how it influences the perception of light colour. Sub-study 3 included further design factors, such as directed and omnidirectional light sources and CCT (2700 and 4000 K), and most of the light sources were frosted. The study comprised four separate experimental set-ups where i) CCT and luminous flux were varied for omnidirectional light sources with R_a/CRI ≥ 80; ii) light distribution angle and CCT were varied for light sources with luminous flux 470 lm and R_a/CRI ≥ 80; iii) luminous flux and R_a/CRI were varied for frosted light sources with omnidirectional light and CCT 2700 K; and iv) CCT and R_a/CRI were varied for frosted light sources with omnidirectional light and luminous flux 470 lm.

All the lighting products included in the sub-studies represented consumer products of white LED lighting found in retail stores.

3-3- Experimental Settings

The studies were carried out in a multi-sensory laboratory and in a research villa, both situated at RISE Research Institutes of Sweden in Borås, Sweden. The multi-sensory laboratory comprises 12 individual test booths designed according to ISO 8589:2010 [58]. In accordance with the ISO standard, the walls of the booths were painted white, and the ceiling was made of white Styrofoam. The test booths were designed to eliminate light interference from the surrounding and nearby booths. Glare protection was added to all booths for tests in sub-studies 2 and 3 (pendant light sources) due to the type of light sources used, while no glare protection was applied in sub-study 1 (recessed spotlights). The booths were equipped with the items to be viewed in the assessments, which were carefully chosen depending on the purpose of the test. For sub-study 1, a frame with colour charts, partly covered by glass, and a magazine were used. For sub-studies 2 and 3, a black vase and a gold-coloured paper bow were added to generate a larger variety of shadows and reflections. In each booth, the position of the observer’s chair was fixed.

The research villa was used as a real context in sub-study 1. It is a full-scale test facility, established in 2014, and used for developing energy efficient and smart housing solutions. The villa was built like a real home but is flexible regarding certain technical solutions and equipped with measuring equipment to enable detailed measurements and studies in a realistic but still somewhat controlled environment. In sub-study 1, two of the (office) rooms were used to perform analytical sensory assessments. The experimental set-up replicated the set-up from the laboratory as far as possible; a white cloth was used to represent the white tabletop, and the windows were covered to minimize daylight interference. Three light sources were installed in each room, and two panellists made assessments simultaneously in each room.

3-4- Choice of Attributes, Training and Calibration

In order for the panel to be able to make analytical (i.e., non-subjective) assessments, the first steps involved the training and calibration of the panel. The training aims at establishing a common set of sensory attributes to be assessed (here perceived light qualities), as well as common scales for each attribute. Depending on the purpose of the sensory assessment, different types of scales may be used [51]. In this case, the attributes were assessed on unipolar line-scales 0-100, anchored at 10 (indicating "little") and 90 (indicating "to a great extent"). The line scale provides more freedom to express sensory perception compared to scales with discrete values. However, the anchor points are used to give the panellists some guidance and, as in this case, can be placed a small distance from both ends of the scale to counteract the panellists’ tendency to not use the full width of the scale in their assessments. Unipolar scales, where one attribute is assessed at a time, are recommended to avoid uncertainties concerning which qualities are opposite to each other or when the intensity of a quality can differ in either direction from a neutral or ideal value, which is the case for bipolar scales [13, 59]. Training assessments were performed for two lighting products from the experimental set-up using an iterative process. Definitions and scales were revised until the analytical panel achieved consensus.

The agreed light-related attributes and their definitions are found in Table 1 (sub-study 1) and Table 2 (sub-studies 2 and 3). The attributes of sub-study 1 were based on previous tests reported in Boork et al. [15]. For sub-studies 2 and 3, the attributes centred around the new concepts of light colour (reddish, bluish, yellowish, and greenish), as well as the introduction of the concepts of diffuse and distinct light, and the correlation with shadows and sparkles/reflections.

Table 1. **Attributes and definitions used in the two assessments in sub-study 1 in 2016 (laboratory and real context)**

Attribute	Definition
Glare	Degree of glare – eye irritation. Look from the bottom to the top towards one of the booth corners (i.e. do not look directly at the light source). Move your head and look straight at the corner.
Flicker	Degree of flicker. Look at the text that is posted on the wall where the wall and ceiling meet.
Yellowness of the light source	Degree of yellowness. Look at the text that is posted on the wall where the wall and ceiling meet.
Non-uniformity	Light non-uniformity on the entire rear wall. Little = completely even light distribution/gradient. To a great extent = shady and non-uniform/sharp transition between dark and bright areas.
Sharpness of the shadow at the frame	The sharpness of the dominant shadow on the tabletop from the left side of the picture frame assessed at the bottom corner at the height of the rear side of the picture frame.
Sharpness of the frame's shadow at the back edge	The sharpness and clarity of the dominant shadow of the picture frame on the tabletop, assessed near the wall where the table meets the wall.
Multiple shadows	Degree of multiple shadows from the picture frame assessed near the wall where the table meets the wall. To a great extent = several well-defined shadows.
Reflection on the table	Degree of reflection on the tabletop in front of the picture frame with glass, near the picture frame, and when varying the position of your body.
Reflection from magazine	*The panellists were instructed to turn to a certain page in the magazine.* Fold the left hand page under the magazine, lift the magazine and look at the picture on the upper edge. Assess the strength/degree of reflection in the picture. Assess maximum reflection.
Contrast in magazine	*The panellists were instructed to turn to a certain page in the magazine and read a part of the text (the body of an advertisement)*. Leave the magazine lying on the table. Assess the contrast as a measure of readability.
Red (colour saturation)	Look at the colour chart in the picture frame without glass. Assess colour saturation. Look at one colour at a time by covering the other colours.
Blue (colour saturation)	Look at the colour chart in the picture frame without glass. Assess colour saturation. Look at one colour at a time by covering the other colours.
Green (colour saturation)	Look at the colour chart in the picture frame without glass. Assess colour saturation. Look at one colour at a time by covering the other colours.
Yellow (colour saturation)	Look at the colour chart in the picture frame without glass. Assess colour saturation. Look at one colour at a time by covering the other colours.

Table 2. **Attributes and definitions used in the assessments in sub-studies 2 and 3 in 2017 and 2018**

Attribute	Definition
Light colour, warm	To what extent is the light experienced as warm. Assess the whole scene. Look at the walls.
Light colour, reddish	To what extent is the light experienced to shift towards red.
Light colour, bluish	To what extent is the light experienced to shift towards blue.
Light colour, greenish	To what extent is the light experienced to shift towards green.
Light colour, yellowish	To what extent is the light experienced to shift towards yellow.
Darkness of shadow	Experience of the darkness of (the whole) shadow on the tabletop. Look at the back of the picture frame.
Sharpness of the shadow at the frame	The sharpness of the dominant shadow on the tabletop of the left side of the picture frame, 3 cm from the front edge of the frame at the height of the rear side of the picture frame.
Sharpness of the frame's shadow at the back edge	The sharpness of the dominant shadow of the picture frame on the tabletop, near the wall where the table meets the wall.
Multiple shadows	Degree of multiple shadows on the left side of the picture frame, near the wall where the table meets the wall. To a great extent = several well-defined shadows.
Character of light, diffuse	To what extent is the light in the booth experienced as diffuse. Assess the whole scene. Look at the walls and tabletop.
Sparkles/reflections	Look at the top of the gold-coloured bow and assess the intensity of the sparkles/reflections that are created where you see the clearest reflection.
Reflection on the table	Degree of reflection on the tabletop in front of the picture frame with glass, near the picture frame and when varying the position of your body.
Reflection from magazine	*The panellists were instructed to turn to a certain page in the magazine.* Fold the left hand page under the magazine, lift the magazine and look at the picture on the upper edge. Assess the strength/degree of reflection in the picture. Assess maximum reflection.
Character of light, distinct	To what extent is the light in the booth experienced as distinct. Assess the whole scene. Look at the walls and tabletop.

3-5-Assessments and Adaptation

The next phase was the assessment of the lighting products, where each panellist entered the test booth in a predefined order to assess the previously agreed attributes of the particular lighting product installed in the booth. All products were assessed by all panellists in triplicate and in a randomized order. In order to minimize the risk of preconceptions, the panellists were not informed about the technical product specifications nor the types of lighting products, and they were not allowed to look directly at the light source. The adaptation time before each assessment was 60 seconds. To counteract dark adaptation, which is the rather slow process of people adjusting to a darker environment, there were no sources of daylight in the test room. In addition, the ambient lighting of the room was at a similar light level to that in the test booths, and the lighting in the room was switched off before each assessment. All panellists started their assessments at the same time, and when one panellist was ready with a particular product, he/she left the room until all panellists were finished. The assessments were recorded on paper for later analysis.

3-6-Statistical Analysis

The data from the sensory assessments in the sub-studies were analysed using descriptive statistics, that is, mean values and standard deviations were calculated for all the assessments by all panellists (triplicate assessments x no. of panellists) of a certain attribute of a specific lighting product. To find out whether the lighting products within the data sets differed significantly regarding the assessed attributes, two-way ANOVAs (analysis of variance) were performed with products and panellists as fixed factors. Principal component analyses were carried out to give overviews of the results (using PanelCheck V1.4.2, Nofima Norway). Following up on the ANOVAs, post hoc tests were performed by applying Bonferroni's pairwise comparison test on the attributes, where significant differences were found ($p \leq 0.05$) to identify which products differed significantly for each attribute. The pairwise comparison tests were carried out both for individual data sets and conjointly for data sets (lab and real contexts).

Pearson correlation coefficients were calculated to find co-variations both within and between sensory data sets, which is how the assessments of attributes co-vary with each other. The significant level was set to $p < 0.05$. Regression analyses were performed to analyse the impact of the properties of the lighting products (the design factors) on the panellists' assessments. The properties were included as independent factors and the data from the assessments as dependent factors. IBM SPSS, version 27, was used for the statistical evaluations.

3-6-1-Quality Analysis of the Assessments

The quality of the assessments was analysed based on each panellist's ability to repeat his/her assessments and to distinguish between the lighting products. This was studied for each attribute and for each test by performing a two-way analysis of variance (ANOVA) of the mean squared error (MSE) and the p-value of each panellist's assessments (using PanelCheck, version 1.4.2, Nofima). Low MSEs (good repeatability) and low p-values (good discrimination between products) indicate the robustness of the sensory assessments and were achieved for most of the attributes assessed in the three sub-studies.

3-7-Physical Measurements

In all sub-studies, three products of each type were used to assess the products in triplicate, since variations associated with production may occur. Physical measurements were performed in connection with the sensory assessments in order to verify that the product properties were equal within a certain range of error, to assess their compliance with the product specification, and to identify variations associated with different test environments (laboratory versus reality). Luminance and illuminance were measured with a photometer (Hagner S4), while spectra and colour parameters were collected using a handheld spectrometer (Metrue SIM-2).

The main deviations identified by the physical measurements include:

- Sub-study 1, the measurements showed deviations in illuminance between the laboratory (average between 596-1199 lux) and real context (163-353 lux). A larger deviation in colour rendering index was identified for the product type with an older light emitting technique (average $R_a < 90$) compared to the other product types (average $R_a > 90$).
- Sub-study 2, one type of product was found to have a much lower colour rendering index (average $R_a = 72.0$ compared to $R_a > 82$ for the other types of products). Another finding was that the CCT values for the 4000 K light sources ranged from 3836 K to 4278 K (average for each type).
- Sub-study 3, the measured physical data did not reveal any significant deviations.

4- Results and Analysis

The results from the sensory assessments will now be presented in terms of how the perceived light qualities *light colour* and *diffuse* and *distinct light* can be described (*RQ1*) and how different product properties influence these qualities (*RQ2*). This is followed by the findings from the comparison between the assessments performed in a more realistic environment and in a laboratory setting (*RQ3*).

4-1-Light Colour

Light colour is significant for the experience of light, but detailed descriptions are lacking. Light colour is frequently described as being synonymous with the physically measured colour temperature. As a potential contribution to the development of measures that can better describe perceived light colour, the new concepts of reddish light colour, bluish light colour, yellowish light colour and greenish light colour were introduced and tested. In order to explore how suitable these new concepts were, their assessments in relation to the assessment of warm light colour (a measure used in previous sensory tests) were analysed, as well as how they related to each other and the other attributes assessed. How various properties of the tested lighting products influenced the perception of the light colour was also investigated.

The results revealed that reddish and yellowish light colour correlated positively with warm light colour, whilst bluish and greenish light colour correlated negatively (see Table 3). Bluish and yellowish light colour demonstrated strong correlations in both sub-studies (sub-study 2 and 3), whereas greenish light colour showed moderate correlations. For reddish light colour, the test in sub-study 2 showed a moderate correlation, and the test in sub-study 3 showed a strong correlation.

Table 3. Correlations for concepts related to light colour, results from tests performed in sub-studies 2 and 3 (significant level $p < 0.05$)

Correlations (Pearson's r) ($p < 0.05$)	Reddish light colour		Bluish light colour		Greenish light colour		Yellowish light colour	
	Sub-studies		Sub-studies		Sub-studies		Sub-studies	
	2	3	2	3	2	3	2	3
Warm light colour	0.54	0.79	-0.74	-0.79	-0.56	-0.46	0.82	0.89
Reddish light colour	-	-	-0.53	-0.52	-0.30	-0.25	0.54	0.76
Bluish light colour	-	-	-	-	0.56	0.62	-0.60	-0.68
Greenish light colour	-	-	-	-	-	-	-0.42	-0.32
Yellowish light colour	-	-	-	-	-	-	-	-

Regarding the correlations between the new concepts, the reddish and yellowish light colours correlated positively with each other and negatively to the bluish and greenish light colours; however, the correlations varied in strength. A strong positive correlation was found between the assessments of reddish and yellowish light colour, at least in the test in sub-study 3, see Table 3, and a moderate correlation between the two in the test in sub-study 2. The strongest negative correlation was found between bluish and yellowish light colour. The weakest correlation was obtained for the assessments of greenish and reddish light colour, followed by the correlation between greenish and yellowish light colour.

There were also a number of significant correlations between the new concepts and the other attributes (list of attributes included in the sub-studies can be found in the Methodology section). However, there were no strong correlations (Pearson's $r \leq |\pm 0.25|$).

Regarding the ***product properties*** of the light sources that influenced the assessment of the different concepts related to light colour, the correlated colour temperature, CCT, clearly showed a significant effect for all the concepts except greenish light colour, see Table 4. The assessments of greenish light colour were affected in sub-study 2, but not in the experimental set-ups in sub-study 3. The principal component analysis showed that the lower the CCT, the higher the warmer light colour concepts (i.e., light colours warm, reddish and yellowish) were assessed.

Table 4. Significance levels for regressions of the effect of product properties on assessed concepts of light colour, results from tests performed in sub-studies 2 and 3. A value of 0 or close to 0 indicates a significant effect, while NS indicates no significant effect ($p > 0.10$)

Significance levels	CCT				Clear/frosted	Distribution angle		Luminous flux		Ra/CRI	
	Sub-studies				Sub-study	Sub-studies		Sub-study		Sub-study	
	2	3			2	2	3	3		3	
		Set-ups						Set-ups		Set-ups	
		i	ii	iv				i	ii	iii	iv
Warm light colour	0.00	0.03	0.01	0.04	NS	0.10	0.06	NS	NS	0.09	NS
Reddish light colour	0.00	0.06	0.04	0.06	NS	NS	NS	NS	0.05	NS	NS
Bluish light colour	0.00	0.03	0.07	0.05	NS	NS	NS	NS	NS	NS	NS
Greenish light colour	0.00	0.10	NS	NS	NS	NS	NS	NS	NS	NS	NS
Yellowish light colour	0.00	0.04	0.04	0.04	NS	0.08	NS	NS	NS	0.09	NS

Other product properties demonstrated little or no impact. The luminous flux showed only a significant effect for the light colour reddish in experimental set-up iii but not in set-up i, while the other light colour concepts were unaffected. The distribution angle had only a moderate effect (the significant level was higher than 0.05) for light colour warm and yellowish (sub-study 2). In addition, the colour rendering index, R_a/CRI, did not affect the assessments to any great extent, with only some influence seen in one experimental set-up (iii) for light colour warm and yellowish. The type of glass in the light sources (clear or frosted) demonstrated no effect.

4-2-Diffuse and Distinct Light

In order to better describe the experiences of even light with little contrast and varied light with soft contrast, the concepts of diffuse and distinct light were introduced and evaluated in the sensory assessments. Since contrasts are created by shadows, reflections, and sparkles, the association between the assessments of diffuse and distinct light and the assessments of shadows, reflections, and sparkles were investigated. How the different properties of the tested lighting products affected the perception of diffuse and distinct light was also explored.

The results demonstrated that diffuse and distinct were very strongly negatively correlated with each other (Pearson's r was -0.93 in sub-study 2 and -0.97 in sub-study 3, $p < 0.05$), which implied that diffuse and distinct were opposites for these tests. Further, diffuse correlated negatively to the shadows and distinct correlated positively (see Table 5). The darkness of the shadow had a strong correlation in both sub-studies, whereas multiple shadows showed much weaker correlations. For the other shadow attributes, the correlations were stronger in sub-study 3's test and weaker in sub-study 2's test. Table 5 shows that diffuse correlated negatively with the assessed attributes for reflections/sparkles and distinct correlated positively. Most of the correlations proved to be strong.

Table 5. Correlations for diffuse and distinct light with shadows and reflections/sparkles, results from tests performed in sub-studies 2 and 3 (significant level $p < 0.05$)

Correlations (Pearson's r) ($p < 0.05$)	Diffuse	Distinct	Diffuse	Distinct
	Sub-study 2		Sub-study 3	
Shadows				
- Darkness of shadow	-0.83	0.82	-0.81	0.81
- Sharpness of shadow at the frame	-0.43	0.41	-0.76	0.77
- Sharpness of shadow of the frame at the back edge	-0.56	0.58	-0.88	0.88
- Multiple shadows	-0.37	0.35	-0.49	0.48
Reflections/sparkles				
- Reflections/sparkles	-0.73	0.77	-0.72	0.74
- Reflection from magazine	-0.76	0.79	-0.71	0.73
- Reflection on the tabletop	-0.63	0.67	-0.74	0.77

Product properties that influenced the assessed light qualities of diffuse and distinct were the correlated colour temperature, CCT, and the distribution angle (see Table 6). However, CCT demonstrated quite diverse results when comparing the tests performed in sub-studies 2 and 3. On the one hand, the principal component analysis for sub-study 2 indicated that the light sources with a lower CCT appeared to create a more diffuse light. On the other hand, none of the experimental set-ups in sub-study 3 showed any significant effect from CCT. For the distribution angle, the significance levels differed between the sub-studies, being lower than 0.05 in sub-study 2. Omnidirectional light sources seemed to create a more diffuse light according to the principal component analysis. Whether the light sources were clear or frosted did not affect the perception of diffuse and distinct (tested in sub-study 2); nor did the luminous flux and colour rendering index, R_a/CRI (sub-study 3) have any effect.

Table 6. Significance levels for regressions of the effect of product properties on assessed concepts of diffuse and distinct light, results from tests performed in sub-studies 2 and 3. A value of 0 or close to 0 indicates a significant effect, while NS indicates no significant effect ($p > 0.10$).

Significance levels	CCT				Clear/frosted	Distribution angle		Luminous flux		R_a/CRI	
	Sub-studies				Sub-study	Sub-studies		Sub-study		Sub-study	
	2	3			2	2	3	3		3	
		Set-ups						Set-ups		Set-ups	
		i	ii	iv				i	iii	iii	iv
Diffuse	0.00	NS	NS	NS	NS	0.00	0.08	NS	NS	NS	NS
Distinct	0.00	NS	NS	NS	NS	0.00	0.08	NS	NS	NS	NS

4-3-Laboratory versus Reality

This sub-study verified the applicability of using analytical sensory analysis in the assessment of lighting products by examining how assessments were affected by being performed in a more realistic, but still rather controlled, context compared to laboratory settings. The consistency of the assessments of the different attributes for the same lighting products was investigated by analysing the results of the two tests (laboratory and real context) in sub-study 1, and for the two environments by statistically comparing the assessments of the different lighting products as well as correlating the assessments for each attribute.

Overall, the results from the laboratory and the real context corresponded well, which can be seen in Figure 2, where the mean values from the sensory assessments of the 14 attributes for the four different types of lighting products are shown. In both the laboratory and the real context tests, the attributes were perceived to differ most for the same products, that is, light sources AA and CC, which was also clearly found in the principal component analysis. It was mainly the attributes of the light sources' yellowness and text contrast (contrast in a magazine) that stood out most noticeably regarding the demonstration of significant differences between the mean values for the different lighting products, both in the laboratory and in the real context (ANOVA and Bonferroni's pairwise comparison). As shown in Table 7, assessments for these attributes correlated positively, with a correlation coefficient of 0.74 for yellowness and 0.59 for text contrast. Although not as clear, yellow (colour saturation) was another attribute that revealed significant differences between the mean values for the light sources both in the laboratory and in the real context. The correlation between the assessed attributes in the two environments was moderate (Pearson's r was 0.50, Table 7).

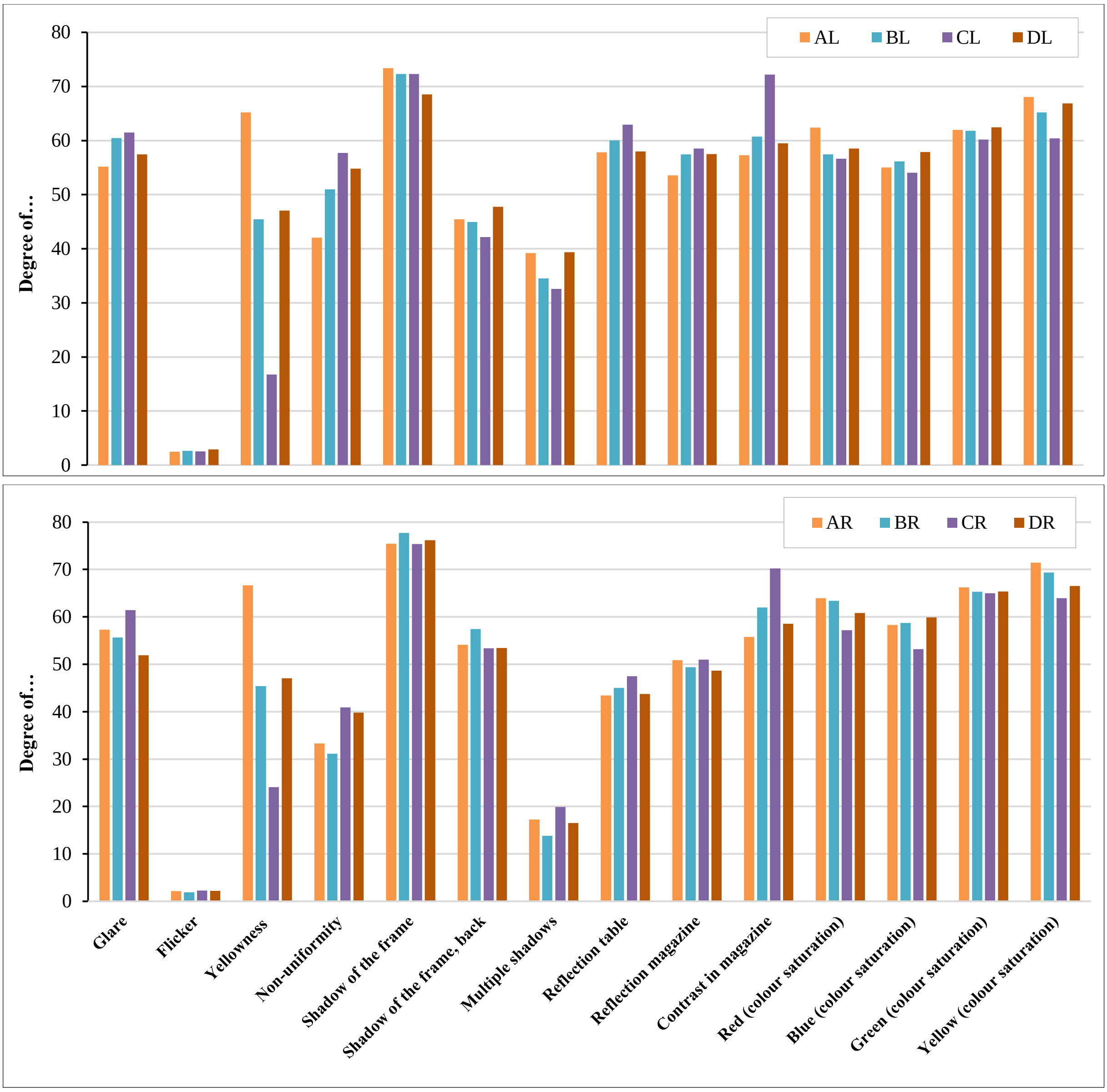

Figure 2. **Mean values (on a scale 0-100) of the assessed attributes for four lighting products performed in laboratory settings (L, top graph) and in the real context (R, bottom graph). Lighting products sub-study 1: AL/R (2700 K, 510 lm), BL/R (3000 K, 560 lm), CL/R (4000 K, 600 lm), DL/R (3000 K, 340 lm, old electronics).**

Table 7. Correlations for assessments in the laboratory compared to real context for attributes with a significance of p ≤ 0.05 (sub-study 1)

Attributes	Correlations (Pearson's *r*) ($p \leq 0.05$)
Flicker[a]	0.75
Yellowness of the light source	0.74
Red (colour saturation)	0.63
Blue (colour saturation)	0.61
Contrast in magazine	0.59
Green (colour saturation)	0.57
Sharpness of shadow at the frame	0.51
Yellow (colour saturation)	0.50
Sharpness of frame's shadow at the back edge	0.45
Glare	0.41

[a] Note that flicker was rated very low by almost all panellists for all products, and in both the laboratory and in the real context (Figure 2), hence a strong correlation was anticipated.

For some attributes, however, differences were found between the assessments in the two environments for the same light sources (Bonferroni's pairwise comparison test was performed for the laboratory and real context conjointly). This applied to the attributes of non-uniformity, multiple shadows, and reflection on the tabletop (for all four light sources). The attribute of the frame's shadow at the back edge was assessed differently for two products (BB and CC). A weaker correlation was also seen between the assessments of this shadow in the two environments (Pearson's *r* was 0.45, Table 7).

5- Discussion

This paper investigates how user-centric measures of the perceived light qualities of lighting products can be described. The focus has been on the light qualities *light colour* and *diffuse* and *distinct light*. Concepts to describe these qualities have been explored, as well as how the product properties of the light sources affect the perception of the light. The applicability of using the sensory method in a real context has also been investigated. The main findings of this paper are discussed below in relation to previous research. The studies in this paper have been exploratory in nature since they applied sensory methodology and analytical panels to produce non-subjective descriptions of the perceived light qualities in question. In general, there are few studies with similar approaches, so in-depth comparisons with previous research results are mostly not relevant. An overwhelming majority of previous studies have focused not just on light sources but on entire light environments and, instead of sensory experiences, have investigated relationships between the eye's sensitivity to different light qualities and photometric quantities.

5-1-Towards Greater Diversity in the Description of Perceived Light Colour

In this paper, the new concepts of reddish, bluish, yellowish, and greenish-light colour were introduced and assessed using sensory analysis in two sub-studies. The results, showing that reddish and yellowish light colour correlated positively with warm light colour and that bluish and greenish light colour correlated negatively, were anticipated since reddish/red and yellowish/yellow are considered warm colours [35]. Bluish/blue and greenish/green are, on the other hand, considered cool colours. The results indicate the suitability of these new concepts. Similarly, the reddish and yellowish light colours correlated positively with each other and negatively with the bluish and greenish light colours. The directions of the correlations were expected considering the colours typically perceived to be warmer (red and yellow) and those perceived to be cooler (blue and green). However, the results were not as clear as one might expect since, for example, reddish and bluish light colours only moderately correlated negatively. This may indicate that certain lights can be perceived to shift in both the bluish and reddish directions. Alternatively, this may point to a need for the training of the panel to be further developed, where the panellists need to be given clearer instructions to use the full width of the scale (0-100) in their assessments. In other words, if the extremes (0, 100) on the scales are not used, two opposite attributes will not be assessed as exclusive, although they will be perceived as such.

Furthermore, the results showed that greenish light colour seemed to be the most difficult concept to assess. The *weak* negative correlation between greenish and reddish light colours was surprising since, in the field of colour, they are seen as opponent colours, meaning that colours cannot be both reddish and greenish [33]. One possible explanation is that green is not actually perceived as such a cool colour, which indicates that the traditional concepts for describing light colours as warm, neutral, or cool are not sufficient to be able to fully comprehend people's experiences of light colour. If one looks at how colours are named in different languages, it can be seen that they are not always grouped into warm (plus white) and cool (plus black) categories. For instance, there appear to be languages with categories that include both yellow and green [60]. In addition, people speaking different languages have a lower consensus regarding what is referred to as green compared to, for example, blue. This might partly explain the difficulty of assessing greenish light colour in our studies.

The concepts of reddish, bluish, yellowish, and greenish light colours also appear in other studies. For example, they are initially included in the tests in [61]; however, the concepts are considered too difficult for the participants to assess. In particular, the bluishness of the light was not that clearly understood. To account for potential difficulties in assessing the new concepts, the panellists' training was a crucial part of the studies in this paper. Other studies have used different metrics and approaches to capture the perception of light colour of white light sources. For instance, Rea & Freyssinier [62] used the metric of *perceived tint* in white illumination, meaning the light's perceived hue and degree of hue, and they developed models from psychophysical experiments to depict the tint. Other metrics commonly relate to the assessment of the whiteness of the light; for example, the white points of different colour temperatures [31] or the colour temperature of perceived neutral or unique white [61, 63], which do not always coincide with the light distribution from an ideal blackbody. Preferences for different compositions of white light are also frequently studied (e.g., [64]), where people seem to prefer white light below the ideal blackbody curve [65]. Although these studies have different approaches to the sub-studies presented in this paper, previous research also confirms that there is no straightforward connection between variations in colour temperature and the perception of light colour. In conclusion, describing light colour, or related qualities allows for more diversity than the concepts commonly used today.

5-1-1-Influence of the Properties of Light Sources on Perceived Light Colour

Regarding the influence of the properties of the light sources on the perceived light colour, this paper found that the correlated colour temperatures of the light sources (2700 and 4000 K) significantly affected the assessments of the light colour concepts, as anticipated; that is, the lower the colour temperature, the higher the warmer light colour concepts were assessed. On the other hand, the findings for the greenish light colour were ambiguous since some set-ups showed an influence and others did not, which again indicates that the descriptions of light colour as warm or cool are not sufficient.

The other product properties demonstrated little or no impact on the light colour concepts. For instance, the luminous flux (250 and 400 lm) did not influence the assessed light colour concepts, except for the reddish light colour in one experimental set-up. Previous research assessing the effect of light levels on the perception of white light shows ambiguous results. For example, no consistent differences between various light levels on the perception of warm, cool, and neutral white lights were found in Davis et al. [61]. On the other hand, in Smet et al. [63], luminance levels were seen to affect the perception of the whiteness of light. The diverging results might stem from the fact that the studies have different designs and test conditions. For instance, the range within which different product properties, such as light levels, are evaluated cannot be ruled out as impacting the results. In our sub-study, we still had a relatively small range in light levels, especially if one compares extreme ranges from daylight levels to very low light levels, which have a large impact on human vision and adaptation ability.

Another example from the present studies is the colour rendering index ($\geq$ 80 and $\geq$ 90), which did not have a significant impact on the assessment of light colour. For the consumer products examined in this paper, a minimum Ra value of 80 is common in indoor environments, hence the chosen values in the assessments. One explanation for the lack of detectable impact from CRI could be that the span between the colour rendering indexes needs to be greater in order for the human eye to perceive clearer differences. However, Lee and Yoon [38] reports an effect on the acceptance of office lights of CRIs that varied from below and above 80, and with similar spans to that in our sub-study. Another explanation may be that there are additional colour characteristics of the light sources that influence the perception more considerably. Other studies, such as Royer et al. [49], emphasize that the span of colour rendition characteristics is important to consider in the experimental design when performing research on subjective evaluations of colour rendition. It also states that by focusing only on CIE Ra, other characteristics affecting the colour rendition might be missed. With the extended colour rendering system TM-30, which is now being developed and is increasingly being used in some parts of the world, the possibility for controlling, as well as varying, several colour rendition characteristics in a research study is improved (see Royer [37]).

5-2-Describing the Character of the Light as Diffuse or Distinct

The concepts of diffuse and distinct were introduced in the studies in this paper as a way to describe the character of light with different degrees of contrast between lighter and darker areas. The sensory assessments demonstrated that these concepts could satisfactorily capture the light qualities created by variations in shadows, reflections, and sparkles; diffuse correlated negatively with the shadow and reflections/sparkles attributes, while distinct correlated positively. The concepts correlated to the assessed attributes as anticipated, although the correlations varied in strength. There were generally stronger correlations in the later sub-study (sub-study 3), which may be explained by the fact that this was the second time the panellists assessed these new concepts. The applicability of the use of the concepts diffuse and distinct was further strengthened by the strong negative correlation between the two.

The concepts of diffuse and distinct have not been commonly included in previous methods used for assessing the qualities of light. An exception is Flynn et al. [5], where the perception of a room with different lighting arrangements was assessed by a group of participants. One of several qualities rated was the visual impression of distinct, which was paired with the term vague on a bipolar rating scale. This type of scale differs from the unipolar scale used to assess the attributes in the present studies, meaning that distinct was not paired with diffuse on the same scale but was instead rated on a separate scale. Nevertheless, the results of the present studies showed that diffuse and distinct were also perceived as opposite concepts (strong negative correlation). Linguistically, diffuse and distinct are not such clear opposites as, for instance, vague and distinct, and participants did not find the concept of diffuse easy to grasp. However, the term vague possibly has a slightly negative association that is not so apparent for diffuse.

Experience shows that the presence of light contrasts, creating moderate variations in light, is often perceived as pleasant [6, 66]. On the other hand, large variations in light contrast can cause discomfort [67]. Hence, standards provide recommendations for how much, for example, the illuminance may vary for different surfaces, such as in task areas and the surrounding areas in offices [16]. The experience of variations in illuminance is also affected by the degree of gradual change in light, where soft contrasts between luminant surfaces and surrounding surfaces are preferable [6]. Contrasts also affect a number of other qualities and may even affect the perceived light level in a room [19, 68], which can be used to reduce the amount of energy used for lighting.

In the present studies, variations and contrasts in the light were created by shadows, reflections, and sparkles, which can all be perceived as both positive and negative qualities. Within lighting design, the interaction and gradation between shadows and light are emphasized as being very important for the experience of an environment [69, 70]. The context plays a large role in whether shadows are perceived as disturbing and reducing visibility or whether the shadows enhance impressions and highlight objects, shapes and materials [6]. Further, sharp reflections are typically associated with impaired visual comfort and something that should be avoided, but they can also be used in a positive way by reflecting and emphasizing objects, often then referred to as highlights [6]. A closely associated quality is what is referred to in the literature as specular reflections or sparkles. One way to achieve sparkles is by directing lighting at shiny and metallic surfaces, making them stand out from their immediate surroundings [71, 72]. Glare from light sources is generally something to avoid, but sparkle has been called "the good glare" in studies examining and producing sparkles with very small, bright light sources, which is another way of generating this quality [73, 74]. Appealing phenomena that create reflections and sparkles can be easily found in nature, such as the stars twinkling in the dark night sky or the sunlight glittering on the surface of water. These are qualities that are imitated in many industries, such as in cars and cosmetics, to increase the attractiveness of their products [72]. This is similar to increasing the attractiveness and pleasantness of light environments.

In conclusion, the presence and variation of shadows, reflections, and sparkles creating contrasts in light have a high impact on the character of the light. Such light characters only appear when there are objects and surfaces in a space, meaning that a completely empty space cannot produce these qualities. In our studies, a picture frame, a gold-coloured bow, and a vase were used to generate a variety of shadows and reflections in order to capture contrast. It is possible that set-ups comprising other items, materials, and shapes may further improve the assessment of the character of light.

5-2-1-Influence of the Properties of Light Sources on the Perception of Diffuse and Distinct Light

The assessments of diffuse and distinct were shown to be most clearly affected by the distribution angle of the light sources. As expected, omnidirectional light sources seemed to create more diffuse light. In Flynn et al. [5], different distribution characteristics did not show the same obvious effect on the visual impression of distinct and vague at the same illumination level; however, the distribution characteristics did not differ as clearly as in the present studies.

The correlated colour temperature demonstrated an ambiguous effect on the perception of diffuse and distinct light, while the other product properties, including the luminous flux, did not show any effect. The latter contradicted the findings of Flynn et al. [5], where the visual impression of distinct was graded higher at a higher illumination level.

Unexpectedly, the type of glass in the light source (clear or frosted) demonstrated no effect on diffuse and distinct. Nevertheless, clear and frosted light sources may become less relevant with the advancement of LED technology, which creates new opportunities for the design of light sources and luminaries compared to the older, phased-out incandescent light bulbs. This means that light sources cannot unambiguously be identified as either clear or frosted.

5-3-Moving out of the Laboratory

Performing tests on consumer products in a laboratory setting is always associated with certain limitations in comparison with the uncontrolled real context in which the products are used. For lighting products, the experience of light qualities in real environments is affected by natural distractions, such as an interior's design and daylight. On the other hand, the laboratory setting provides a controlled environment where specific properties of the products and qualities of the light can be isolated and objectively assessed, which characterises tests in laboratories in general [75].

To verify the applicability of using analytical sensory analysis to assess lighting products, this paper examined how assessments were affected by being performed in a more realistic, but still rather controlled, context compared to laboratory settings. The comparison of assessments performed in test booths and in office rooms in a research villa (real context) demonstrated overall consistency. However, the results showed that care should be taken with regard to how to assess certain attributes and how the results are interpreted in a more diverse environment where more aspects, such as the design of a room, cannot be controlled. This was the case in this particular sub-study for some of the shadow and reflection attributes, as well as the degree of non-uniformity of light on the wall.

The consistency between the results of the two settings (in this paper) shows that the knowledge generated about perceived light qualities and specific attributes is valid not only in laboratory settings, but also in real applications (e.g., office environments). Previous research on the performance of tests in booths compared to a more realistic room shows that the results appear to be compatible when other factors are similar [49]. However, studies where direct comparisons are made, for example, by statistical calculations as in this paper, are not common. For instance, in a study by Dangol et al. [76] on user acceptance of office lighting, findings in small-scale tests performed in booths were verified in full-scale mock-up office rooms, but no statistical analysis was reported.

One intention of this sub-study was to build on the method development of previous studies that apply sensory methodology to the perception of lighting [15] by verifying the applicability of the method to real environments. The results in terms of consistency, therefore, also broaden the scope of application of the method. This may, for example, open up the possibility of performing tests on products that are not suited for the laboratory, such as larger and more complex lighting systems.

5-4-The Importance of Adaptation

One aspect related to the experimental procedure is adaptation time, which is particularly relevant for the assessment of perceived light colour. Royer et al. [49] highlight that different results can be obtained depending on how long the participants are allowed to adapt before the assessment takes place. In the studies in this paper, the adaptation time before each assessment was 60 seconds, in accordance with previous tests that apply analytical sensory assessment to lighting [15]. Various adaptation periods are reported in the literature, for example, 60 seconds [77], 10 minutes [78], and 20 minutes [79]. Royer et al. [49] state that chromatic adaptation is 90% complete after 60 to 310 seconds if the luminance level is constant. This might suggest that the adaptation time in this paper is possibly on the shorter end of the range. However, the measures taken to reduce the influence of different light conditions inside and outside the test booths in the present sensory studies are thought to be sufficient. The importance of considering light and dark adaptation for colour perception tests is also pointed out for colour rendition [49], as well as for how humans register intensities of light [68]. The latter could have an impact on the assessments related to diffuse and distinct in this paper.

5-5-Contribution and Relevance

The studies included in this paper contribute to the establishment of a common terminology for perceived light qualities that is largely lacking in both industry and research. This complements the physical measures, which are often based on the lighting standards that currently dominate lighting planning. A particular value of the studies in this paper is that they have focused on investigating and developing descriptive, *analytical (objective)*, user-centric measures of perceived light qualities, unlike most perception-related research on light that studies human preferences (e.g., [39, 49, 64, 80]). Perceptions, and not least preferences, are strongly influenced by several factors, for example, cultural aspects [55, 56], which should not affect the analytical experience in the same way. Instead, analytical studies aim to capture and describe people's objective visual perceptions without evaluating whether people like or dislike the light qualities, which is believed to be especially useful when developing a general terminology. Aspects such as cultural influences as well as inter-observer differences (e.g. [28, 81]), are mitigated by using an analytical panel that is trained and calibrated before the assessments are carried out; that is, the panellists establish a common set of attributes to be assessed according to their definitions, as well as common scales for each attribute. Nevertheless, hedonic (subjective) and analytical (objective) studies can be associated and can complement each other by carrying out studies where the concepts are linked to people's desires and preferences in certain situations and contexts [13]. This approach for capturing several dimensions of perceived qualities of products has long been used in other trades, not least the food industry [51].

One major strength of this paper is that it is part of the research project Perceptual Metrics for Lighting Design, which comprises several related sub-studies. The sub-studies are based on input from industry partners, first and foremost lighting experts and practitioners, but also property owners and clients, which means that the research questions and findings are highly relevant for industry. In parallel with the sub-studies on the sensory analysis of light sources, other sub-studies within the project are conducted with a focus on perceived light qualities in light environments—both in full-scale environments and in scale models of a room. The exchange of experience and findings between these parallel studies strengthens their relevance since similar questions can be examined using various approaches. For example, tests are performed in a series of scale models that are based on a typology where principles for lighting and colour schemes are combined to illustrate how the two fundamental factors *light level* and *contrasts* interact to create different characters of the light [82, 83]. How the light is distributed to produce contrasts is strongly connected to the perception of diffuse and distinct light created by different light sources, as presented in this paper.

The studies in this paper used commonly available consumer products. In the longer term, the acquired knowledge, together with the other related sub-studies in the research project Perceptual Metrics for Lighting Design, will contribute to providing guidance for professionals and consumers in choosing suitable light sources to achieve the desired light qualities.

6- Conclusions and Further Studies

This paper explores user-centric measures of perceived light qualities of lighting products using sensory analysis. Since this method is not typically used for lighting, the studies add a new approach to describing perceived light qualities that neither lighting research nor the industry have explored so far. One main conclusion is that the perception of light qualities can be described using concepts that are in addition to those currently used. First, the studies demonstrate that the concepts of reddish, bluish, yellowish, and greenish are suitable for describing light colour. Although the colour temperature of the lighting products strongly influences the perception of light colour, the relation is not entirely straightforward, as seen for the greenish light colour. It is, therefore, not sufficient to only consider the colour temperature in order to describe perceived light quality—an assumption made in many previous studies. Further verification of the new concepts of light colour is required, possibly also introducing additional colours, since the studies indicate that certain lights shift towards more than one colour. Second, the concepts of diffuse and distinct are shown to satisfactorily capture the light qualities created by variations in shadows, reflections, and sparkles. As expected, the distribution angle of the light sources was the most decisive product property affecting the perception of these light qualities. The current studies demonstrate one way of describing this light character in relation to the presence of contrasts. With strong support from previous experience and research, and if created with care, this can improve light environments—both in terms of the visual experience and the required light levels.

Another conclusion is that analytical sensory analysis is also applicable for assessing the perception of lighting in real environments. This finding has two implications. First, knowledge generated in the laboratory is also valid in a more realistic context. Second, lighting systems that are not suitable for testing in a laboratory setting can still be assessed with analytical sensory analysis in another environment. A further development of the method's applicability would be to verify if the consistency between the two settings persists for other types of lighting products, as well as for additional light qualities.

7- Declarations

7-1- Author Contributions

Conceptualization, C.H., M.B., and J.E.; methodology, J.E., and K.W.; validation, C.H., and M.B.; formal analysis, C.H. and K.W.; investigation, C.H., M.B., J.E., and K.W.; resources, C.H., M.B., J.E., and K.W.; data curation, K.W.; writing—original draft preparation, C.H.; writing—review and editing, M.B., J.E., and K.W.; supervision, C.H. and M.B.; project administration, C.H.; funding acquisition, C.H., M.B., and J.E. All authors have read and agreed to the published version of the manuscript.

7-2- Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7-3- Funding

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7-5- Institutional Review Board Statement

Not applicable.

7-6- Informed Consent Statement

The Swedish Ethics Review Act 'applies to research carried out in Sweden if the research includes the processing of sensitive personal data'. This study includes questions of perceived light qualities which, according to the Data Protection Ordinance, are not classified as sensitive personal data. In accordance with the General Data Protection Regulation (GDPR), no responses on the evaluation forms used in the current studies can be traced to or used to identify any individual. All participants received written and oral information about the studies and the study products and gave informed consent to participate.

7-7- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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