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Effect of Lamp Spectrum on Perception of Comfort and Safety

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ABSTRACT

In addition to improving visibility and providing orientation, public lighting is expected to contribute to the perception of comfort and safety of people outside after dark. At present, high-pressure sodium (HPS) lamps are widely used in outdoor applications due to their high efficacy and reliable lifetime. Their use however, comes at the expense of good color rendering and accurate color appearance. Recently developed ceramic metal halide (CMH) lamps provide many of the advantages of HPS in addition to natural white light and significantly better color rendering.

In this paper, results of quantitative research conducted in three European countries on the effect of lamp spectrum on visual performance and the perception of safety and comfort outdoors are presented. The results consistently show that at comparable light levels, the same people perceive areas illuminated with high quality white light to be brighter, safer and more comfortable than the same neighborhood illuminated with yellowish high-pressure sodium lighting.

Keywords

Perception of safety and comfort, outdoor lighting, street lighting, white light

INTRODUCTION

Artificial outdoor lighting can play several important roles. In addition to enabling safe movement, improving visibility and providing orientation, public lighting is increasingly used to contribute to the perception of safety and comfort of people outside after dark. The perception of safety, comfort and appreciation of an outdoor area can be strongly influenced by the lighting used to illuminate it.

Without conditions that ensure safe movement, it would not be possible for people to walk on the street, and without conditions that ensure a general perception of safety, people might choose not to walk on the streets. Factors contributing to safe movement after dark include visual orientation and the ability to detect obstacles on the pavement which may otherwise be a trip hazard. Factors contributing to the perception of safety include absence of glare, perception of brightness in the area and the ability to recognise the expression or faces of other road users at a distance sufficient to take avoiding action if necessary. Previous investigations have suggested that people want to be able to recognize strangers from a distance of 4 m in order to feel comfortable [1]. However it is extremely likely that this "comfort zone" distance varies significantly from one person to another and also depending on the familiarity of the environment. Improving the distance for and ease of facial recognition might contribute to increasing the feeling of safety and security of pedestrians and especially for those who feel most vulnerable. There is certainly interaction between these factors. In general a lighting scheme designed to meet one of these needs, such as recognition of faces and expressions may well go some way to meeting all of them [2].

At present, high-pressure sodium (HPS) lamps are widely used in outdoor applications due to their high efficacy and reliable lifetime. Their use however, comes at the expense of good color rendering (CRI of HPS ~25) and accurate color appearance. Recently developed ceramic metal halide (CMH) lamps provide many of the advantages of HPS in addition to natural white light and significantly better color rendering (CRI > 60). Related benefits of these lamps for the residents and pedestrians in the areas illuminated by them might include greater ease of facial recognition and color identification. Indeed, an earlier laboratory study conducted by Raynham et al. [3] concluded that twice the illuminance level of HPS is required to achieve the same facial recognition distance as with white compact fluorescent light sources at typical nighttime outdoor lighting levels. The advantages of high quality white light for facial recognition is already taken advantage of in the British standard for road lighting, BS5489:2003, which allows a lower lighting level to be used in residential areas if the color rendering index (CRI) of the source used is over 60 [4,5]. Color provides important visual information. Color differentiation and identification can contribute to one's ability to recognize faces or identify one's car, for example. Moreover, in the case of reporting a criminal act, accurate color naming can provide key information about the color of the suspected person's clothing or automobile.

Research conducted by Boyce et al. in New York City and Albany, NY suggests that there is a link in the public mind between the perception of safety of an area after dark and the perception of brightness of that area [6]. Of course the perception of safety in an area depends on many factors which are not related to lighting. Nevertheless, there is a need for residential areas to appear appropriately brightly illuminated at night to support the perceived safety of people in the area at night.

Fotios and Cheal used brightness ratings, brightness rankings and brightness matching to compare the effect of lamp spectrum on the perceived brightness in a variety of laboratory tests. Their results showed that at equal illuminance, lighting from white metal halide (MH) and compact fluorescent light sources were perceived to be significantly brighter than from yellowish HPS. Moreover, they found that at the typical illuminance levels encountered on urban streets (2 – 15 Lux), the same perception of brightness was achieved when the illuminance ratio of metal halide to HPS (MH/HPS) was ~0.73 [7,8]. These results were consistent with early laboratory studies conducted by Rea et al. in which subjects were asked to adjust the illuminance on a scale model scene illuminated with a HPS source until it matched the brightness of the same scene illuminated by a MH source. At illuminance of 0.1 and 1 cd/m^2, the illuminance ratio (MH/HPS) found to achieve an equal perception of brightness was 0.71 [9]. This means that people perceived scenes illuminated with metal halide sources to be equally bright as scenes illuminated with HPS sources when the measured illuminance was ~29% lower for the MH scene. In more recent field tests conducted by Rea et al.[10], respondents stood in the middle of a street between two luminaires and compared the perception of brightness of opposite ends of the street by alternatively looking at the street scenes illuminated by each luminaire. Subjects compared a variety of scenes where one part of the test street was illuminated with HPS at levels between ~5 – ~15 Lux and the opposing direction of the street was illuminated with CMH source also between ~5 – ~15 Lux. Subjects were given written questionnaires and for each pair of lighting conditions, they were asked to make a forced choice for the lighting condition, under which they would feel safer to walk at night and under which the street and surroundings as well as objects placed on the pavement appeared brighter. The test included pairs of lighting conditions where the ratios of illuminance on the scene illuminated with CMH to the illuminance on the scene illuminated with HPS (CMH/HPS) varied between 0.33 – 3. Interpolation of the results suggested that an illuminance ratio of CMH/HPS of 0.79 was required to create an equal perception of brightness and a ratio of 0.66 was required to create an equal perception of safety [10]. This opens up the opportunity to maintain the same perception of safety with CMH lamps while reducing the light level.

In this paper, results of field tests conducted in actual urban streets in the Netherlands, Spain and the United Kingdom on the effect of lamp spectrum on the perception of safety and comfort are presented. The goal of the research was to determine how end-users evaluate the outdoor lighting in their neighborhoods before and after it was changed from yellow high pressure sodium (~2000K) to warm white CDO 2800K or neutral white CDO 4200K street lighting and vice versa, as well as how this change affected their perception of safety and comfort and their appreciation of the neighborhood. At the same time, objective measurements of the performance for facial recognition and color identification were compared under yellow and warm or neutral white light. Altogether, over 300 residents participated in the experiments under both yellow and white light.

TECHNICAL PROPERTIES OF LAMPS USED

The lamps used in the experiments were based on high pressure sodium (HPS) and ceramic metal halide (CMH) technologies. Some properties of the lamps are listed in Table 1.

Table 1: Correlated color temperature (CCT) and color rendering index (CRI) of HPS and CMH sources used in experiments

Technology	Commercial Name	CCT (K)	CRI
HPS	SON T	2000	25
CMH	Master City White 2800 CDO-TT 2800K	2800	83
CMH	Master City White 4200 CDO-TT 4200K	4200	90

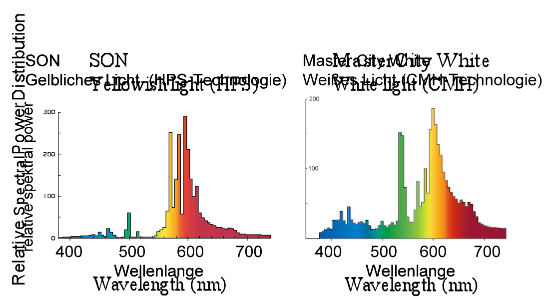


Figure 1: Spectrum of SON (based on HPS technology) and Master City White 2800K (CMH technology)

RESEARCH SET-UP

Research was conducted in Eindhoven, NL, Navalcarnero, Spain and St. Helens, UK by IPM International as part of a large quantitative study commissioned by Philips Lighting to evaluate how residents experienced the street lighting in their neighborhoods before and after it is changed from yellow HPS (~2000K) to warm white (~2800K) light as well as how this change affects their perception of safety and comfort and their appreciation of their neighborhoods.

As evident from Table 2, the tests in the UK were conducted after those in the NL and in Spain. Additional tests were conducted in different streets in St. Helens, UK, where the lighting was changed from (1) HPS to neutral white light (CDO 4200K), (2) from neutral white light (CDO 4200K) to warm white light (CDO 2800K) and (3) from warm white light (CDO 2800K) to HPS. The latter was done to check whether or not changes seen were due to the fact that residents expected certain changes due to a change in lighting. In the UK, each participant performed the test under both lighting conditions in one area. Different participants performed the tests in the different areas.

The people responsible for public lighting in the respective cities identified possible locations where the lighting could be changed according to the research schedule. One of our requirements of the test areas was that they were safe. This was necessary to ensure that the researchers could conduct interviews and tests at night with minimal risk. The residents were sent or shown a letter informing them that tests were being conducted to evaluate the perception of safety of the area after dark. There was no mention of lighting or the commissioner (i.e. Philips) in the letters.

The number of different respondents who participated in the tests in each area is shown in Table 2. The respondents were recruited from people living in the vicinity, but not in the actual streets in the experimental area. The split over gender and age group (below and above 40 years) is shown in table 3. One of the recruitment criteria was that the respondents walked or biked outside after dark at least three times a week.

The test involved individual face-to-face interviews during which a detailed questionnaire was filled in. In addition, objective measurements of visual performance were conducted. Each test lasted ~45 minutes. A *mixed research design* was used in Eindhoven and Spain, meaning that some of the respondents (55 and 60 in the case of the Netherlands and Spain respectively) participated in the test both under the initial lighting condition as well as after the lighting had been changed (i.e. "before and after") while others only participated in the subjective evaluations after the lighting had been changed (see Table 2). This *mixed design* enabled the detection of artifacts since people might become more sensitive to lighting after they have been interviewed about it the first time. The lighting was changed soon after the first set of interviews ("before" interviews) were completed and the "after" interviews were started at least 3 weeks after installation of the new lighting. There was no extra maintenance (e.g. cleaning) when the lamps were changed.

During the face-to-face interviews, the respondents were asked to

1. Rate their perception of safety and comfort in the test area on a 5-pt scale
2. Rate the importance of street lighting to their perception of safety and comfort
3. List the most important aspects of lighting for them and to evaluate the street lighting in the test area against these and other aspects

Subsequently, the respondents were explicitly asked to

4. Make various comparisons using a 7-point scale with respect to the previous lighting condition.

Visual performance was evaluated on the basis of the distance to recognize faces and colors. During the facial recognition test, the researchers stood with their back towards the closest pole so that the picture was only illuminated from the distant neighboring pole. The researchers held pictures with the faces of well-known personalities for the particular country in front of themselves. The pictures were printed on non-glossy A4 paper so that the size of the face was approximately life-sized. A total of 8 different pictures were used. The pictures were divided into two groups of 4 pictures. Half of the residents were shown one group of 4 pictures under the initial lighting, and the second group of pictures after the lighting had been changed. The other half of the participants was shown the pictures under the reverse lighting conditions so that all pictures were observed under both lighting conditions. The order of the 4 pictures shown was randomized among the different participants. Only the respondents in the "before + after" group did the facial recognition test, and a within-subject analysis was done to compare the performance under the different light sources.

The poles used and the position at which the researcher stood relative to the pole was chosen under the initial lighting. The vertical illuminance at the position of the pictures was measured under both lighting conditions.

The protocol for the facial recognition test was as follows. As shown schematically in figure 2, the test person started walking slowly from a distance of ~15 m towards the researcher holding the picture. They were instructed to stop and say as soon as they were close enough to

1. Identify the gender of the person on the picture
2. See the picture well enough to guess the identity of the person and
3. See the person well enough to be sure of their identity

It was stressed that the focus was on seeing the picture well enough to guess or be sure of the identity of the person on the picture even if the respondent did not know the person or remember their name. All three distances were recorded.

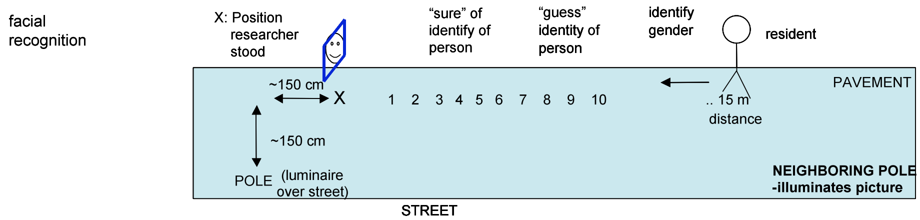


Figure 2: Schematic of set-up used in facial recognition and color identification tests

Table 2: Summary of the number of respondents and timing of evaluations done in 3 European cities

		Installed Lamps and Test Dates				Evaluations Done	
Location	Nr. different respondents	Initial Lighting Condition	Test Date 1 Initial Condition	Lighting after Lamp Change	Test Date 2	Comparison of Visual Performance	Subjective Evaluation
Eindhoven, NL	55	SON	March 2006	CDO 2800K	April 2006	√	√
	56			CDO 2800K	April 2006		√
Navalcarnero, Spain	60	SON	April 2007	CDO 2800K	May 2007	√	√
	60			CDO 2800K	May 2007		√
St. Helens, UK	30	SON	November '08	CDO 2800K	January '09	√	√
	33	SON	November '08	CDO 4200K	January '09	√	√
	31	CDO 2800K	November '08	SON	January '09	√	√
	31	CDO 4200K	November '08	CDO 2800K	January '09	√	√

Table 3: Summary showing split over gender and age group

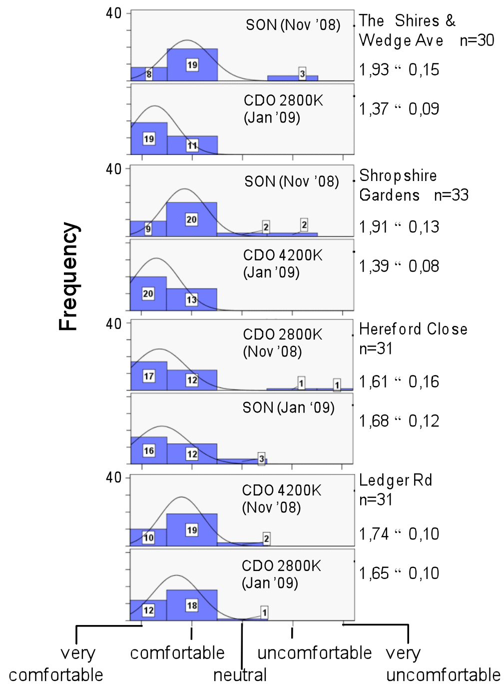
	Eindhoven, NL (n=111)		Navalcarnero, Spain (n=120)		St. Helens, UK (n=125)		All 3 countries (n=356)	
	% male	% female	% male	% female	% male	% female	% male	% female
≤ 40	15	12	24	27	21	20	20	20
> 40	50	24	27	20	24	35	33	26

RESULTS

The results were analyzed separately for each country. In all three countries, the most important aspect of street lighting given by the respondents was the "brightness" of the illuminated area. Consistent with studies referenced in the introduction, a higher perceived brightness of the street and pavement contributes to a higher perception of safety. Since one of the requirements of the areas chosen was that it was safe, it is not surprising that independent of the lighting, people felt relatively safe in all test areas.

As illustrated by the histograms of the results from the UK, substantially more people felt *very* comfortable when the same area was illuminated with warm or neutral white light compared to with SON (see figure 3). This trend was also seen in Eindhoven and in Navalcarnero. The mean and standard error of the mean is written next to the plots in figure 3 and also by similar plots in later figures.

Table 4 summarizes how respondents in the UK answered various questions on a 5-point scale regarding their perception of comfort in the area, the quality of the lighting and the effect of the street lighting on their perception of safety and brightness of the area. The mean for the above evaluations are given. Paired-sample T-tests (confidence interval 95%) were used to evaluate if the mean of the ratings were different or not under the first and second lighting condition. There is a difference when the corresponding value in Sig.(1-2) column in Table 4 is less than 0,05.



Question: How do you feel about the area here? After sunset, please rate how you feel on a 5 point scale from very comfortable/very much at ease to very uncomfortable/ very uneasy. very comfortable = 1, very uncomfortable = 5

Figure 3: Plots showing how respondents in St. Helens, UK rated the perception of comfort before and after the lighting had been changed.

The respondents were asked the same questions under both lighting conditions. Moreover, at the point where they were asked these questions under condition 1, there was no discussion that the lighting would be changed and under condition 2, there was no mention that the lighting had been changed.

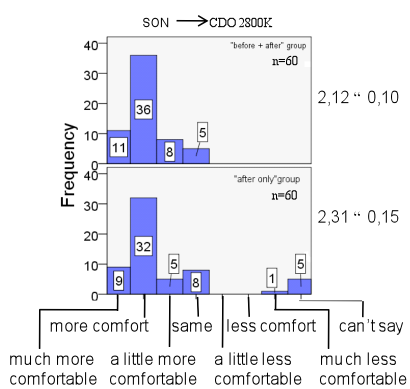
As seen in table 4, there were no statistically significant differences regarding how the same people rated the area and effect of the street lighting on their perception of safety when the lighting was changed from CDO 4200K to CDO 2800K. However, when the lights were changed from SON to either CDO 2800K or CDO 4200K, the perception of safety, comfort, brightness and light quality was improved.

When the lights were changed from CDO 2800K to SON, there was a statistically significant reduction in the rated light quality, brightness of the area and the effect of lighting on the perception of safety. In particular, the brightness of the area was rated to be "just right" with CDO 2800K and CDO 4200K, whereas it was rated to be "too dark" with SON. Even when the lighting in Hereford Close was changed from CDO 2800K to new SON lamps, the area with the new SON lamps was evaluated to be "too dark" (table 4). Even though a statistically significant difference in the perception of comfort was found when the lighting was changed from SON to CDO 2800K, there was no statistically significant difference found regarding the perception of comfort of the area when the reverse change was made (i.e. from CDO 2800K to SON). This might suggests that there is an enhancement in the subjective ratings after changing the street lighting. Nevertheless, the results taken together consistently indicate that for pedestrians, streets illuminated with white light are perceived to be brighter and safer and at least equal but often more comfortable than the same streets with SON.

Table 4: Summary of ratings for different lighting conditions in St. Helens

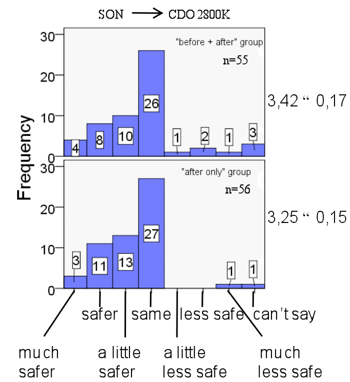
		Mean Rating			
Questions:	Cond. 1 → Cond. 2	Cond. 1	Cond. 2	Diff. (1-2)	Sig. (1-2)
How do you feel about this area here? After sunset, do you feel: very comfortable / at ease (1) ⇔ very uncomfortable / uneasy (5)?	SON → CDO 2800K	1,93	1,37	0,567	0,001
	SON → CDO 4200K	1,91	1,39	0,515	0,000
	CDO 2800K → SON	1,61	1,68	-0,07	0,861
	CDO 4200K → CDO 2800K	1,74	1,65	0,097	0,374
Now I would like you to tell me what you think of the lighting in terms of its quality: By quality I mean nice light, good color. Do you feel that it is: 1 (very pleasant) ⇔ 5 (very unpleasant)	SON → CDO 2800K	2,40	1,67	0,733	0,000
	SON → CDO 4200K	2,61	1,30	1,303	0,000
	CDO 2800K → SON	1,94	2,58	-0,645	0,009
	CDO 4200K → CDO 2800K	1,77	1,94	-0,161	0,258
And now I would like to know whether the lighting here makes you feel safe or not. Does it make you feel: 1 (very safe) ⇔ 5 (very unsafe)	SON → CDO 2800K	2,20	1,33	0,867	0,000
	SON → CDO 4200K	2,06	1,33	0,727	0,000
	CDO 2800K → SON	1,52	2,06	-0,548	0,003
	CDO 4200K → CDO 2800K	1,65	1,68	-0,032	0,572
And how do you rate the brightness of the area. For you personally, is it: 1 (much too bright) ⇔ 5 (much too dark). 3 = just right.	SON → CDO 2800K	3,38	2,90	0,483	0,000
	SON → CDO 4200K	3,34	3,00	0,345	0,016
	CDO 2800K → SON	3,00	3,61	-0,613	0,000
	CDO 4200K → CDO 2800K	2,97	3,03	-0,065	0,489

After answering the questions shown in table 4, the respondents were asked during the second condition if they had noticed any recent changes in the test area. As mentioned in the research set-up, the respondents in general did not live in the streets where the lighting had been changed, but in the vicinity. About 50% of the Dutch respondents in the "before + after" group spontaneously mentioned the street lighting had been changed, as did about 40% in the Dutch "after only" group. By comparison, in Spain, ~77% of the respondents in the "before + after" group and ~50% of the respondents in the "after only" group spontaneously mentioned that the street lighting had been changed. In St. Helens, ~85% of the respondents noticed the change from SON to CDO and ~55% still noticed the change from CDO 4200K to CDO 2800 K. When triggered to look at the street lighting, the majority of respondents, including those in the "after only" groups in the Netherlands and Spain who had not spontaneously mentioned the street lighting, eventually reported that the color of the street lights had changed or that brighter street lights had been installed. Since the street lighting in the Netherlands and Spain was changed on a commonly used connecting road in the residential area, even those respondents who did not do the test under the first condition (i.e. "after only" group) were familiar with the test area. In the UK, where smaller residential streets were used, all of the respondents did the test under the initial as well as the second lighting condition. Thus the vast majority of respondents could make an evaluation as to whether or not they felt equally comfortable (or safe etc.), or less or more so than before. The comparison was done using a 7-point scale, where "no difference" was assigned a value of 4. A one-sample T-test was used to check the difference between the mean of the distribution and the test value "4" (no difference). In figures 4 – 6, results of some of the responses are graphically shown and in Table 5, a wide range of data is summarized.



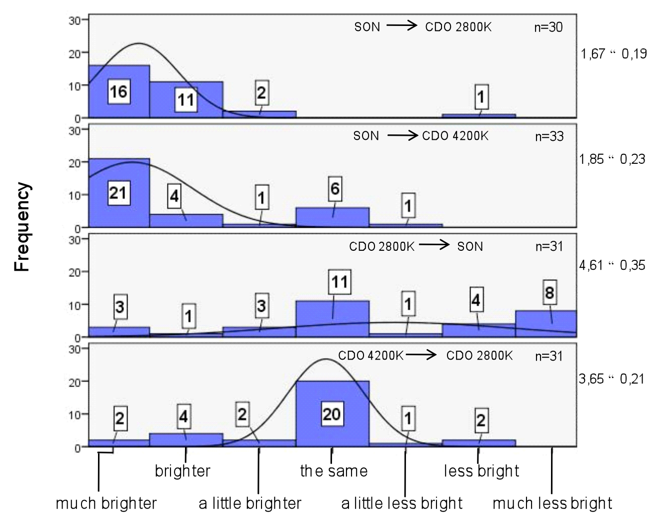
Question: How comfortable is the current street lighting, compared to the street lighting before?
(SON →CDO 2800K, CDO is the "current" lighting)
much more comfortable = 1, the same = 4, much less = 7

Figure 4: Plots showing how respondents in Navalcarnero, Spain, compare the perception of comfort after the lighting was changed to CDO. Mean and std. error of mean is listed.



Question: How does the present lighting compare with the lighting before? Does it make you feel much more safe, the same or much less safe?
(SON →CDO 2800K, CDO is the "present" lighting)

Figure 5: Plots showing how respondents in Eindhoven, NL compare the perception of safety in the test neighborhoods after the lighting had been changed to CDO.
much safer = 1, the same = 4, much less safe = 7



Question: How does the present lighting compare with the lighting before in terms of brightness, quantity of light?

Figure 6: Plots showing how respondents in St. Helens, UK compare the brightness in the test neighborhoods after the lighting had been changed as shown on the plots.
much brighter = 1, the same = 4, much less bright = 7

When specifically asked to compare the lighting, the majority of respondents in all three countries rated the white street lighting to be equally or more comfortable than the yellowish SON street lighting. There were no statistically significant differences between the "before + after" and the "after only" group in either the Netherlands or Spain. The most common reasons given for the increased comfort were related to the ability to see clearer, better and further. The reason most often given by the few respondents who rated the area to be less comfortable after the change to white light was that the area was too brightly lit in their opinion.

Moreover, when the street lighting is changed from yellowish HPS to warm or neutral white CDO, the perception of safety is significantly improved. In the test street in St. Helens, where the lighting was changed from warm white CDO to yellowish SON, the majority of respondents did not report any change in the perceived safety in the area – albeit a few more respondents reported that it had deteriorated. The fact that there was no significant difference in this "before vs. after" test when white CDO was offered first and yellowish HPS offered subsequently might indicate that there is a positive enhancement in the rating of the second lighting condition since respondents might automatically expect an improvement when street lighting is changed. Nevertheless even with this "expected improvement", yellow HPS is not rated better than white light regarding the ambience of perceived safety created. No difference was found between the perceived safety under warm and neutral white light in St. Helens. CDO 4200K was not evaluated in the Netherlands and Spain in this test.

The main reason given in all three countries for the increased perception of safety under white light is related to the higher perception of brightness of the whole area. The majority of respondents perceive the area illuminated with white light to be brighter, even though the measured illuminance level was not increased (Table 6). This is consistent with previous laboratory studies referenced in the introduction.

When the area appeared brighter, most respondents felt that their clarity of sight was improved and this was linked to an improved perception of safety. Though not the subject of this paper, it should be noted that many respondents clearly expressed that they want the area at night to appear "bright", but not "*too* bright". The lighting levels used in the different test locations were typical for the type of urban streets in the particular country and were not perceived as being "*too* bright" by most respondents in the specific area. As seen subsequently in Table 6, the installed lighting levels varied significantly in the different countries, with the highest level being in the Spanish test location.

In summary, in all three test locations, most respondents appreciated the increased perception of brightness achieved by using white CDO street lighting. This was achieved at the same installed power and comparable illuminance levels.

Table 5: Summary of various evaluations comparing the second to the first lighting condition

Question	Land	Group	Cond. 1 → Cond. 2	Mean	Std. Error Mean	Test Value =4 Sig. (2-tailed)
Now I would like to ask you how comfortable and pleasant the present lighting is in your personal opinion? Compared to the lighting before, is it? 1 = much more comfortable 4 = the same 7 = much less comfortable	NL	b+a[1]	SON → CDO 2800K	3,28	0,24	0,004
		a only[2]	SON → CDO 2800K	3,24	0,19	0,000
	Spain	b+a	SON → CDO 2800K	2,12	0,10	0,000
		a only	SON → CDO 2800K	2,31	0,15	0,000
	UK	b+a	SON → CDO 2800K	1,77	0,20	0,000
		b+a	SON → CDO 4200K	1,94	0.17	0,000
		b+a	CDO 2800K → SON	4,06	0,37	0,861
		b+a	CDO 4200K → CDO 2800K	3,45	0,21	0.013
And how about safety? How does the present lighting compare with the lighting before? Does it make you feel 1 = much safer 4 = the same 7 = much less safe	NL	b+a	SON → CDO 2800K	3,42	0,17	0,002
		a only	SON → CDO 2800K	3,25	0,15	0,000
	Spain	b+a	SON → CDO 2800K	2,41	0,11	0,000
		a only	SON → CDO 2800K	2,63	0,13	0,000
	UK	b+a	SON → CDO 2800K	2,07	0,21	0,000
		b+a	SON → CDO 4200K	1,97	0,16	0,000
		b+a	CDO 2800K → SON	4,32	0,28	0,258
		b+a	CDO 4200K → CDO 2800K	3,71	0,18	0,119
And what about the brightness of the area? Does it look 1 = much brighter 4 = the same 7 = much less bright	NL	b+a	SON → CDO 2800K	3,17	0,21	0,000
		a only	SON → CDO 2800K	2,76	0,18	0,000
	Spain	b+a	SON → CDO 2800K	2,08	0,96	0,000
		a only	SON → CDO 2800K	2,35	0,12	0,000
	UK	b+a	SON → CDO 2800K	1,67	0,19	0,000
		b+a	SON → CDO 4200K	1,85	0,23	0,000
		b+a	CDO 2800K → SON	4,61	0,35	0,087
		b+a	CDO 4200K → CDO 2800K	3,65	0,21	0,102

[1]b+a = "before + after"group, [2]a only = "after only" group

In each area, respondents in the "before + after" group performed facial recognition tests under 2 lighting conditions.
In Spain and the Netherlands, the distance at which residents were sure that they could recognize faces on the picture was increased by more than 20% under white light. This objective measurement was consistent with subjective evaluation that faces were easier to recognize under white light.

In tests conducted in the UK, independent of whether the test was first done under white or yellow light, respondents consistently expressed the perception that the clarity of their visibility and ability to see expressions, faces and details was improved under white light sources. However, this was not consistently reflected in the results from the facial recognition tests done in St. Helens. In Hereford Close where the test was first done under CDO 2800K and then under SON, the mean distance for facial recognition was longer under SON. It should also be noted that in Hereford Close, the mean distance for facial recognition under CDO was lower than in other test locations in St. Helens where the vertical illuminance on the pictures were comparable. The reason for this is unclear. Compared to the initial CDO condition, the difference in the mean under the second lighting condition (SON) was just statistically significant. This result might indicate that there was a "learning effect" which contributed to the respondents identifying the pictures from further away in the 2nd lighting condition (even though they were shown different pictures). However, this "improvement" attributed to a learning effect is less than the improvement generally seen when CDO 2800K or CDO 4200K is used instead of SON.

Table 6: Average Distance for Facial Recognition Measured in Tests done in Eindhoven, Navalcarnero and St. Helens

Cond.		Vert. illuminance on picture (Lux)	Dist. to identify person. Mean ± std. Err. Mean (m)	Diff. Mean Cond1-Cond 2 (m)	Sig. Cond 1_2
	Eindhoven, The Netherlands (55 respondents)				
1	SON (yellow)	3.3 ± 0.6	5.4 ± 0.5	-1,2	0,000
2	CDO 2800K (warm white)	1.4 ± 0.4	6.6 ± 0.4		
	% higher with CDO 2800K rel to SON		+ ~22%		
	Navalcarnero, Spain (60 respondents)				
1	SON (yellow)	10 ± 0.7	8.5 ± 0,26	-2,4	0,000
2	CDO 2800K (warm white)	~10	10.9 ± 0,21		
	% higher with CDO 2800K rel to SON		+ ~28%		
	The Shires and Wedge Avenue, St. Helens, UK (30 respondents)				
1	SON (yellow)	~1.6	8.7 ± 0.5	-1,1	0,015
2	CDO 2800K (warm white)	~1.6	9.8 ± 0.4		
	% higher with CDO 2800K rel to SON		+~13%		
	Hereford Close, St. Helens, UK (31 respondents)				
1	CDO 2800K (warm white)	~1.6	7.6 ± 0.5	-1,2	0,047
2	SON (yellow)	~1.6	8.9 ± 0.7		
	% higher with CDO 2800K rel to SON		- ~14%		
	Shropshire Gardens, St. Helens, UK (33 respondents)				
1	SON (yellow)	~0.6	5.7 ± 0.5	-1,8	0,003
2	CDO 4200K (neutral white)	~0.6	7.1 ± 0.6		
	% higher with CDO 2800K rel to SON		+ ~25%		
	Ledger Road, St. Helens, UK (31 respondents)				
1	CDO 4200K (neutral white)	~1.6	9.8 ± 0.5	-1,4	0,040
2	CDO 2800K (warm white)	~1.6	11.3 ± 0.5		
	% higher with CDO 2800 rel to 4200K		+ ~13%		

CONCLUSION AND DISCUSSION

The results presented in this paper are based on quantitative research exploring the effect of lamp spectrum on people's perception of street lighting after dark. The results show that people experience several benefits when high quality white light is used instead of yellowish street lighting. In particular, the perception of brightness, comfort and safety is significantly enhanced in the same area as judged by respondents in three European countries who conducted the tests in areas where the street lighting had been changed from yellowish SON to warm or neutral white CDO lighting. The results of these field tests together with other published results [11, 12] illustrate the limitations of the current practice of using the photopic luminous efficiency function V(λ) at mesopic light levels (i.e. between 0,001 – 3 cd/m^2). V(λ) is used to transform the spectral power distribution of a light source into a single measure of the light level (luminance and illuminance). V(λ) characterizes the spectral sensitivity of foveal cones, which peak at 555nm under photopic lighting conditions (i.e. > ~3 cd/m^2). However, many of the lighting levels encountered on residential streets at night fall within the mesopic range. At mesopic light levels, both rods and cones in the retina may be active. This leads to changes in the spectral sensitivity with changing light levels since the contribution of rods and cones vary with changing light levels in the mesopic region. The peak of the spectral sensitivity of rods is at ~507nm. Therefore for lighting applications at night, the effectiveness of lamps with relatively more short wavelength emission (i.e. white light sources compared to yellow light sources) can be underestimated by the current system of photometry. This is currently being addressed by various technical committees (TC) within the CIE. In particular, CIE TC 1-58 is working to establish the appropriate mesopic sensitivity functions which can serve as the foundation of a system of mesopic photometry based on visual task performance (e.g. detection of objects, speed of detection, identification of the objects). This system is not expected to correlate well with visual assessment of brightness in the mesopic region [13]. However, another technical committee (TC 1-37) is developing a supplementary system of photometry for evaluation of lighting at all lighting levels in terms of brightness.

The use of a more appropriate system of mesopic photometry for the mesopic range can encourage the use of more visually effective and thereby energy efficient lighting and eventually contribute to a safer, more comfortable and pleasant feeling for people outside at night.

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