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Linear LED tubes versus fluorescent lamps: An evaluation

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ABSTRACT

Many manufacturers and distributors of LED tubes claim energy savings of 50% and more when replacing T8 fluorescent tubes with linear LED replacement lamps. Several distributors even pretend that the same visual comfort will be maintained after such a replacement. Optical and electrical parameters of twelve commercially available linear LED tubes have been determined and the evolution in time of these parameters has been monitored. Additionally, a case study is presented in which the fluorescent lamps in a small office room were replaced by LED linear replacement lamps in order to compare the illuminance distribution on the work plane, the glare perception and the overall visual appreciation. According to this study, it is clear that a one-to-one replacement of a classical fluorescent tube by a currently available linear LED lamp might have severe consequences on the lighting quality.

1. Introduction

LED based luminaires are emerging into the market. Properties such as long life, dimmability and variability, unlimited switching, flexible design, high luminous efficacy, compactness and negligible heat transfer in the light beam make solid state lighting an attractive alternative to traditional light sources. LED based systems are not only available for orientation and architectural lighting but more and more for general illumination applications too [1,2]. Today, LED based downlights are outcompeting the traditional compact fluorescent lamps in terms of efficiency and lighting quality [2].

On the other hand, there are many applications where the benefits of using LED products are not obvious. The use of LED tubes as replacement lamp for fluorescent lamps is a typical product causing controversy. Several distributors recommend their products as a superior replacement of conventional T8 fluorescent lamps, mainly focussing on the potential energy savings and long life of the light-emitting diode replacements. However, the lighting quality is often subordinate or ignored [3,4]. Some distributors argue that retrofitted luminaires achieve equal or even larger illumination levels on the task area, even though the luminous flux of the LED replacement is considerably lower, referring to the superior light output ratio (LOR) of the luminaire due to the directionality of LEDs. However, manufacturer data of LED tubes are often limited and incomplete and the overall light distribution of the luminaire after replacement is unknown [3–5]. Above, there is a lack of standardisation and inspection to evaluate SSL products [6], often resulting in overstated and misleading manufacturer performance claims [3] which amplifies the discussion.

In this study, the optical and electrical parameters of twelve commercially available LED linear replacement lamps have been compared and the variation over time of these parameters has been investigated. Furthermore, a case study is presented in which the fluorescent lamps in a small office room have been replaced by LED linear replacement lamps in order to compare the illuminance distribution on the task area. Finally, the performance of LED replacement lamps was investigated and compared with a standard fluorescent T8 lamp in a psychophysical experiment in terms of general lighting quality, colour quality and glare perception.

2. Optical and electrical parameters of LED linear replacement lamps: a bench test comparison of 12 LED tubes

2.1. Methodology

In September 2010, twelve LED tubes of brands distributed on the Belgian market were collected [5]. These lamps are intended for replacement of standard T8 36 W fluorescent lamps. All LED replacement lamps have an integrated driver powered directly from the ac mains power supply.

After lamp stabilization, all relevant initial optical and electrical parameters were measured: real (or active) power P, luminous efficacy, power factor PF, total harmonic current distortion THD_I,

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Table 1
Initial lamp parameters.

Brand	Φ (lm)	*P* (W)	η (lm/W)	*CCT* (K)	*CRI*	*MCRI*	CQS v7.5	PF	THD_I
A	1650	22.8	72.4	4186	90	90	88	0.97	14%
B	1535	23.6	65.0	6876	72	75	72	0.45	192%
C	1595	17.8	89.6	3709	76	83	79	0.82	56%
D	1774	21.2	83.7	4016	69	77	68	0.66	90%
E	754	10.3	73.4	4207	76	85	73	0.48	55%
F	1707	20.9	81.6	3194	65	74	68	0.93	17%
G	1036	15.2	68.2	3307	71	80	68	0.51	162%
H	1437	17.7	81.1	3853	77	85	75	0.96	16%
I	1605	31.6	50.8	3365	88	90	86	0.53	135%
J	920	14.5	63.4	3678	78	87	71	0.84	59%
K	1479	18.3	80.8	4733	65	64	68	0.78	54%
L	1185	17.6	67.3	5329	73	79	72	0.91	22%
Median	1479	17.8	73.4	3853	76	81	72	0.82	55%

luminous flux, luminous intensity distribution, spectrum, correlated colour temperature *CCT*, colour rendering index *CRI*, colour quality scale CQS and memory colour rendering index *MCRI*. The *MCRI* [7] is a new metric that assesses the colour quality of a light source with respect to the memory colours of a set of familiar objects. This metric was found to correlate significantly better at assessing the colour quality of white light sources in terms of visual appreciation than the conventional *CRI* [8]. It should be noted that, while a *CRI* score of approximately 90 is significantly lower than that of a CIE reference illuminant, it is not on the MCRI scale – CIE reference illuminants have scores around 90, while a score of 100 is reserved for a perfect 'memory colour' agreement [7,8].

The NIST CQS is another new metric which correlates better with the visual appreciation of colours compared to the traditional CIE colour rendering index. The CQS is a colour difference based metric which does not penalize chroma enhancement and even rewards chroma [9].

A near-field goniophotometer type Techno Team RIGO801® [10] equipped with an illuminance meter and an image-resolving CCD camera for determining ray data and far field luminous intensity distributions were used to determine the luminous flux and luminous intensity distribution of all lamps. The temperature and relative humidity in the room were controlled within narrow ranges (25 °C ± 1 °C and 32 ± 5% RH). The spectra and resulting *CCT*, *CRI*, CQS and *MCRI* values were determined by using a telescopic measuring head coupled to a spectroradiometer (Oriel®) with an optical fibre. A cooled CCD detector captured the spectral flux after a suitable calibration measurement with a spectral radiance standard. The electrical parameters were measured by a Yokogawa® WT3000 precision power analyser. The sinusoidal supply voltage with a root-mean-square value of 230 V was delivered by a power source type Agilent® 7813B.

2.2. Initial lamp characteristics

The initial lamp parameters as measured are summarized in Table 1. Measurements did not start before the stabilisation time was elapsed. Stable operation was reached when the relative variation of luminous flux was no more than 0.5% within 3 continuous minutes. This criterion guarantees stable thermal conditions.

With the exception of one lamp, all LED tubes draw at least 30% less real power than their fluorescent counterpart. The lamp power is going from 10.3 W to 31.6 W with a median value of 17.8 W, which is half the real power of the fluorescent lamp.

A primary objective of any (re)lighting project should be to fulfil the existing and widely accepted lighting requirements, e.g. the European standard for lighting indoor work places [11]. The luminous flux and the intensity distribution of the replacement lamp are the main factors that determine the lighting level after a relamping. The medium value of the luminous flux of the measured LED tubes is 1479 lm which is only 44% of the luminous flux of a new conventional T8 36 W/830 (about 3350 lm) fluorescent tube of the same dimensions. The spread in luminous flux is rather large, ranging from 754 lm to 1774 lm. Depending on the power consumption of the (electromagnetic) ballast, the lamp-ballast efficacy of a common T8 fluorescent lamp varies between 75–95 lm/W. The median luminous efficacy of the measured LED tubes (with integrated driver) is about 73 lm/W with 5 lamps having an efficacy of more than 80 lm/W. This is comparable with the efficacy of a T8 lamp-ballast combination. As the luminous efficacy of new LED types is still increasing, the lamp-driver efficacy of LED tubes will exceed the lamp-ballast efficacy of standard fluorescent lamps very soon.

The *CRI*, CQSv7.5 and *MCRI* values are determined from the lamp spectra. In all lamps under study, blue LEDs with an individual phosphor layer are used. A typical phosphor white LED spectrum is shown in Fig. 1. It is remarkable that only two out of twelve lamps have a *CRI* higher than 80. According to the European standard for work places [11], lamps with a *CRI* lower than 80 should not be used in indoor workplaces. The two sources, with a *CRI* score higher than 80, also scored highest on the CQS and *MCRI* scales.

If the rated real power of light sources (except for discharge lamps) is less than or equal to 25 W, there are no specific requirements for the current waveform and maximum harmonic current components [12]. As the real power of most LED replacement lamps is lower than 25 W, a non-sinusoidal current may be expected. The extra harmonic current components cause extra losses in electrical cables and transformers which is especially an issue for distribution network companies [13]. For residential electricity customers, the negative impact of harmonic currents is usually marginal. However, for non-residential customers, the harmonic distortion may cause problems when many fluorescent tubes are replaced by LED tubes with high harmonic content. Increased losses and possible

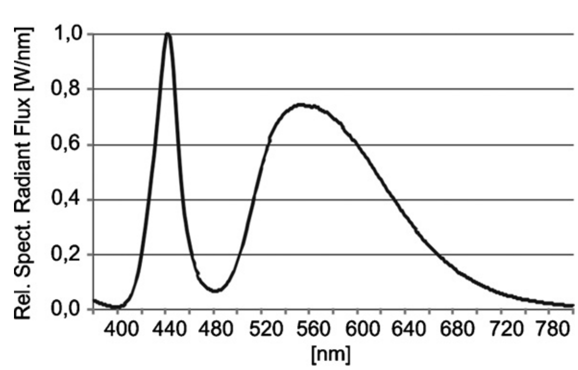

Fig. 1. Spectrum of LED tube (*Brand K*).

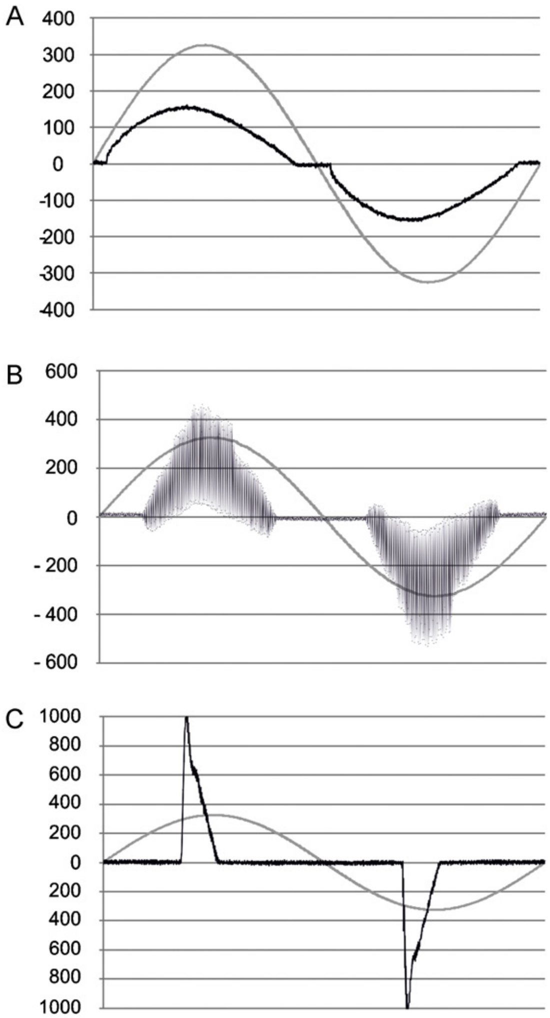

Fig. 2. Current [mA] (black) and voltage [V] (grey line) waveform (top: *Brand A* – middle: *Brand D* – down: *Brand B*).

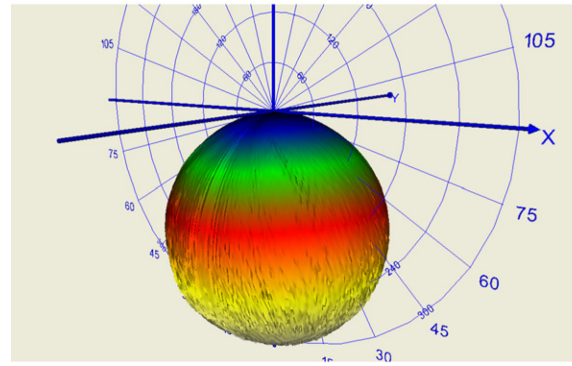

Fig. 3. Luminous intensity distribution (3D) – *Brand K*.

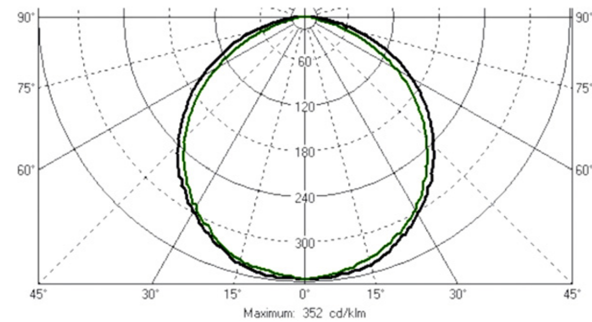

Fig. 4. Luminous intensity distribution C0-180 (black) and C90-270 (green) – *Brand K*. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of the article.)

overloading of transformers and cables, especially of the neutral conductor, are the main concerns [14].

The total harmonic current distortion THD_I is a measure for the harmonic current content. For a sinusoidal supply voltage, the power factor λ is related to the THD_I as (see Appendix A):

$$\lambda = \frac{\cos \varphi_1}{\sqrt{1 + THD_I^2}} \quad (1)$$

Hence, the power factor combines the phase angle φ_1 between the fundamental (50 Hz or 60 Hz) current and voltage component and the harmonic current distortion. The lower λ, the higher the losses in the electrical installation and the higher the risk for harmonic-related problems.

Four lamps under study have a high power factor with values greater than 0.9. On the other hand, the THD_I of three LED tubes exceeds 100%, resulting in a power factor around 0.5. This implies that twice the current is needed to deliver the real power as compared to a lamp drawing a sinusoidal current in phase with the voltage for the same real power. Furthermore, some lamp currents waveforms exhibit a lot of high frequency (>2 kHz) components which might cause electromagnetic interference. Some typical current waveforms are shown in Fig. 2.

As LEDs are lambertian light sources, the luminous intensity pattern of most LED tubes is approximately lambertian as illustrated in Figs. 3 and 4. The luminous intensity distribution of some LED tubes (f.i. *Brand J*) has been modified by secondary optics. To describe the directivity of a light source, the Full Width at Half Maximum (FWHM) angle is often used. The FWHM is the angular separation between the directions at which the intensity has fallen to half its peak value. For an ideal lambertian luminous intensity pattern, the FWHM is 120°.

The FWHM values for all LED tubes under study are mentioned in Table 2. Especially lamp *G* has a small light beam which can have a huge impact on the uniformity of the illumination [3].

Finally, the measured initial lamp characteristics are compared with the manufacturers lamp data (if available) in Table 3.

For the lamps considered, the measured real power is in accordance with the specifications. However, the specified luminous flux and the *CRI* are in many cases strongly overestimated by several distributors.

2.3. Luminous flux maintenance

To evaluate the lumen maintenance, all lamps have been operated at a burning cycle of 3 h. A programmable logic controller switches the lamps in cycles of 2 h and 45 min on and 15 min off [5]. The luminous flux of all lamps was measured at 2000 h intervals. The measured values are divided by the initial luminous flux of the

Table 2
FWHM values.

Brand	FWHM	*Brand*	FWHM
A	115°	G	65°
B	85°	H	115°
C	100°	I	95°
D	115°	J	85°
E	125°	K	120°
F	85°	L	115°

Table 3
Measured lamp characteristics versus manufacturers lamp data.

Brand	Measured characteristics				Manufacturers data			
	Φ (lm)	*P* (W)	*η* (lm/W)	*CRI*	Φ (lm)	*P* (W)	*η* (lm/W)	*CRI*
F	1707	20.9	81.6	65	2042	21.5	95.0	73
G	1036	15.2	68.2	71	1454	15	96.9	>80
H	1437	17.7	81.1	77	1476	17.4	84.8	75
I	1605	31.6	50.8	88	2000	32	62.5	>80
K	1479	18.3	80.8	65	1400	18	77.8	NA
L	1185	17.6	67.3	73	1600	18	88.9	>80

Table 4
Luminous flux maintenance (values expressed as a percentage of the initial luminous flux).

Brand	Initial value (%)	2000 h (%)	4000 h (%)	6000 h (%)	8000 h (%)
A	100	100.5	98.7	95.7	93.0
B	100	97.9	96.9	95.3	95.5
C	100	61.4	37.8	31.4	23.2
D	100	101.1	95.5	89.1	80.9
E	100	85.7	82.5	80.1	78.9
F	100	100.2	94.7	Failure	–
G	100	86.3	73.6	70.3	67.3
H	100	105.7	105.6	105.1	105.4
I	100	102.3	102.6	102.2	101.0
J	100	89.4	65.5	59.7	59.0
K	100	107.1	107.8	105.7	104.5
L	100	103.4	98.1	95.1	94.9

lamp and expressed in Table 4 as a percentage of the initial luminous flux.It is known that the luminous flux of LEDs can increase in the first thousands of burning hours [15]. The results in Table 4 confirm this behaviour. Tubes of brands *C*, *E*, *F*, *G*, and *J* are built up with white through-hole LEDs. It is well known that, despite its relatively low input power, the heat generated in a traditional through-hole LED cannot escape efficiently from the semiconductor element [15]. This explains the (strong) decrease in luminous flux. LED tube *F* reached end of life after 5500 h due to electronic driver failure. For professional applications, a lumen maintenance value of 70% (noted as L_{70}) is typically used as criterion to define the end of life [16]. Nearly all lamps based on through-hole LEDs have reached the end of life after 8000 burning hours. The luminous flux maintenance of LED tubes with SMD (surface mounted device) LEDs is obviously better due to the improved heat transfer. Thermal resistances of SMD packages are indeed up to 50 times smaller than those of through-hole packages [15]. Three lamps maintain their initial luminous flux after 8000 burning hours.The measured real power of all lamps remained almost constant (change between −2% and +1%), as well as all other parameters considered (*CCT*, *CRI*, *PF* and *THD*).

3. Retrofit of a fluorescent luminaire: a field study

3.1. Technical performance

In Fig. 5, a small office room used by the students' union of the Catholic University College KAHO Sint-Lieven is shown. The windowless room is 4 m by 6 m and 2.7 m high. Three outdated T8 luminaires are installed, each with one T8-36 W/840 fluorescent lamp. The fluorescent lamps of all luminaires have been replaced by LED tubes in order to compare the quantity and quality of the illumination before and after replacement. Three brands (*A*, *I* and *K*) of LED tubes with different characteristics were selected. As the individual high-brightness LEDs are visible, the LED tube of *Brand I* can cause glare while LED tube of *Brand A* has a diffuser to limit the glare risk. LED tube of *Brand K* was selected because this lamp has the lowest *CRI* value of all lamps considered.

Replacing a conventional fluorescent lamp by a LED tube with a hemispherical, yet quite different luminance distribution, will change the luminous intensity distribution of the luminaire as well as the illuminance distribution on the task area.

The luminous intensity distribution of the luminaire with four different lamp types was measured under controlled conditions with a near-field goniophotometer (see Section 2.1). New lamps were used and the ferro-magnetic ballast was not removed or bypassed.

- LED tube *Brand A*. The lamp has a diffuser to reduce the high luminance of the individual LEDs. The measured FWHM, *CCT* and *CRI* are 115°, 4186 K and 90, respectively. The measured luminous intensity distribution of the luminaire is shown in Fig. 6a. The *LOR* of the luminaire is 85% and the real power is 23.5 W;
- LED tube *Brand I*. This lamp is made up of only 32, but high-intensity LEDs and has a *CCT* of 3365 K, a *CRI* of 88 and a FWHM of 95°. Fig. 6b shows the luminous intensity distribution of the

Fig. 5. Small office room used by the students' union of KAHO.

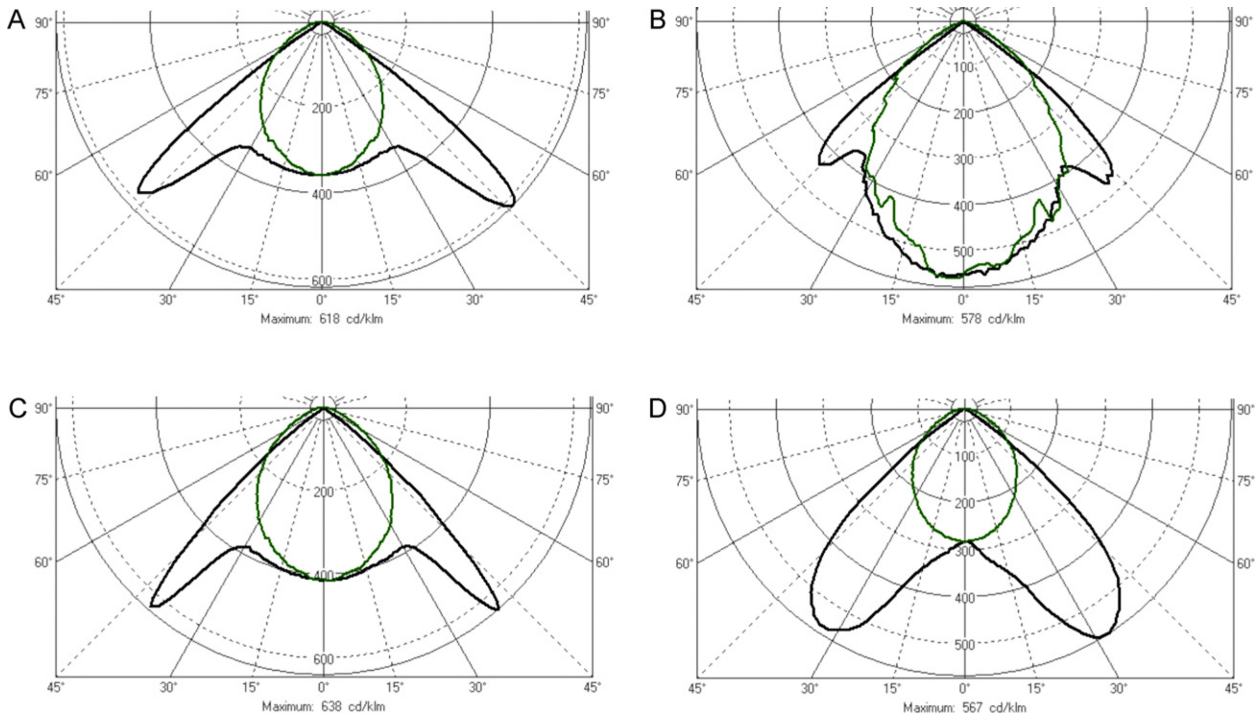

Fig. 6. Measured luminous intensity distributions (in cd/klm green: C90–C270 and black C0–C180). (a) Luminaire with a LED tube with diffuser (*Brand A*). (b) Luminaire with a LED tube with 32 high intensity LEDs (*Brand I*). (c) Luminaire with a LED tube with 360 SMD LEDs (*Brand K*). (d) Luminaire with a fluorescent lamp T8–36 W/840.

luminaire with a measured LOR of 86%. The real power of the luminaire is 32 W;

- LED tube *Brand K* made up of 360 individual SMD LEDs. The FWHM, *CCT* and *CRI* are 120°, 4733 K and 65, respectively. The luminous intensity distribution is shown in Fig. 6c. The real power of the luminaire is 19.7 W;
- A new fluorescent lamp type T8 36 W/840 with a measured *CCT* of 4121 K and *CRI* of 84. The luminous intensity distribution of the luminaire is shown in Fig. 6d. The luminaire efficiency *LOR* is 77%. The real power of the luminaire is 51 *W*. Hence, the old electromagnetic ballast consumes 15 W.

While a fluorescent lamp emits light in all directions, a LED tube is a (lambertian) directional light source emitting light in a downward-hemispherical arrangement (Figs. 3 and 4). Hence, the linear replacement lamps cannot use the luminaire reflector design in the same way as fluorescent lamps do. Therefore, the luminous intensity distribution of the luminaire with an LED tube is considerably different from the luminaire with fluorescent lamp (Fig. 6). On the other hand, the hemispherical radiation of LED linear replacement lamps results in less light losses within the luminaire. In our study, the luminaire efficiency increases from 77% to about 85% after relamping.

For each luminaire–lamp combination, Eulumdat files (.ldt) were generated from near field goniometer measurements and the Rigo Software® [10] and imported in the lighting planning software DIALux® to simulate the light distribution in the room under consideration. The calculated mean illuminance values E_{avg} and uniformity values g_1 (i.e. the minimum divided by the mean illuminance) on the horizontal task area at 0.8 m height are given in Table 5. A wall zone of 0.3 m was used.

Replacing all fluorescent tubes by LED tubes will decrease the power consumption substantially, with energy savings up to 70% (the installation and maintenance costs not considered). However, the mean illuminance will be reduced with about 50% to an unacceptable value. The illuminance values in Table 5 are initial values (depreciation factor equals 1) and will decrease over time, especially if through-hole LEDs have been used (Section 2.3). In this case study, the uniformity is in the same range.

If the original lighting installation would have been designed to comply with the lighting specifications [11] or legal requirements, it is clear that in most cases the modified lighting installation will not provide the same level of illuminance as the original lighting installation and the specified requirements for lighting solutions for work places will not be met anymore.

If the same illuminance value is required after replacement of a fluorescent lamp by a LED tube, the number of installed luminaires must be doubled resulting in a comparable power consumption. Above, the investment and installation costs are high and in most cases, it will not be possible to obtain the original luminaires.

3.2. Visual experiments

The performance of three LED replacement lamps and the standard fluorescent T8 lamp in their application was investigated in a psychophysical experiment in terms of general lighting quality, colour quality and glare. The experimental setup was a delayed paired comparison experiment in the real room situation shown in Fig. 5.

Forty four observers (38 male/6 female), with an average age of 27, participated in the experiments. The subjects, divided in groups of 4–6 persons, had to evaluate all four lamp types. The sequence of the lamps was randomized between different groups. During each lamp replacement, the subjects had to leave the room for several

Table 5
Calculated workplane illuminance.

	$P_{installed}$ (W)	E_{avg} (lx)	g_1
T8	153.6	**278**	0.21
Brand A	70.5	149	0.21
Brand I	95.7	146	0.15
Brand K	59.1	160	0.19

Fig. 7. Abrupt transition from dark to light on the walls (LED tube *Brand I*).

minutes. For each lamp type, the observers were asked to assess the lamp with reference to the previous lamp.

General lighting quality, subdivided in brightness and attractiveness, was assessed for the room in general and for a piece of white paper with text. Colour quality was evaluated in terms of the attractiveness and naturalness of the skin of the observers and a number of coloured objects, such as a yellow bath duck, a smurf, a tomato, a red pepper, blue grapes, a lemon and a cucumber. Perception of glare was investigated for two situations: observers had to assess the glare by looking straight at the lamp above them (direct glare) and by looking around the room in a horizontal plane.

The paired comparison data have been analyzed with the method of Scheffé [17] to obtain a scaling for each lamp type for each of the aspects investigated. The lamp scalings and *CCT*, *CRI* and illuminance (*E*) on the work plane are given in Table 6. The fluorescent lamp is used as reference in this table.

From Table 6, it is immediately clear that the TL source scored the highest on almost all the investigated aspects of lighting. Not surprisingly, the TL – with approximately 80% higher work plane illuminance than the LED tubes – had the highest visual brightness and glare when looking around the room (as all visual scaling are 100). Obviously, the room is perceived darker when the fluorescent lamps are replaced by LED tubes. Adaptation cannot compensate for those large differences in illuminance and luminance. The fluorescent light also had the highest visual attractiveness both in terms of general lighting quality and colour quality. However it should be noted that this observation is due to the low illumination levels rather than an effect attributable to the colour rendering properties of the TL lamp. With some LED tubes, there might be also an abrupt transition from dark to light on the walls (see Fig. 7) which can be perceived disagreeable.

Although, these results indicate that a replacement of a single TL – in an existing luminaire – with a single LED tube could reduce the visual comfort in the room significantly, it is however not clear whether this would still be the case for an equal luminous output and a more uniform lighting on the walls.

However, for the case under investigation, the results presented in Table 6 suggest that the LED tube of *Brand A* would be the best overall choice for a replacement of the fluorescent lamp. Although *Brand K*, which has no diffuser, had a comparable brightness in the room, it scored poorly on glare. Of all the LED tubes, *Brand K* was also found to have the lowest scores for attractiveness and naturalness, which is in line with the *CRI*, CQS and *MCRI* values. LED tubes of *Brand I* had the opposite problem, i.e. comparable or only

Table 6
The *CCT*, *CRI* and illuminance at the work plane and visual scalings for the four lamps.

Lamp type	*CCT* (K)	*CRI*	E at work plane (lx)	Room lighting brightness	Room lighting attractiveness	Text lighting brightness	Text lighting attractiveness	Colour quality naturalness	Colour quality attractiveness	Glare In room	Direct glare
I	3365	88	146	0	52	0	43	31	55	0	79
A	4186	90	149	44	36	40	46	58	69	26	0
K	4733	65	160	42	0	45	0	0	0	84	100
TL	4121	84	278	100	100	100	100	100	100	100	48
Ye[a]				18	32	20	39	7	40	15	56

[a] Ye: Yard stick to evaluate significance of difference between scaling.

slightly worse scores for naturalness and attractiveness, but very low scores for brightness. Even though the room lighting brightness and the text lighting brightness were much less than *Brand A*, problems with direct glare are obvious (see Table 6). It has to be mentioned that only an exploratory study on glare perception was carried out in this study. As existing glare criteria (UGR, VCP) seem not to be applicable for non-uniform stimuli [18], a new glare metric is needed. The new glare evaluation system(s) should take into account both discomfort glare and overhead glare [18].

4. Commercial, economical and juridical aspects

Commercial, economical and juridical aspects have not been considered in this study. Nevertheless, there may be safety and other concerns [19] such as:

- an unsafe situation (electric shock risks) can occur when LED modules are installed;
- the lamp holders of the original luminaire may be overstressed by the weight of the LED tube;
- probably, the converted luminaires will not comply anymore with requirements of the luminaire safety standards (EN 60598-1) and CE mark labelling. In fact, the organization modifying a luminaire should take over the full future responsibility for the luminaire with respect to all aspects (safety, EMC, photometric, . . .);
- the lamp manufacturer's warranty will be void if the adapted luminaire does not comply with lamp safety and performance standards.

5. Conclusions

Luminaires based on phosphor converted white LEDs are more and more attractive for general lighting applications because of the steadily increasing luminous efficacy numbers and the distinctive properties. High-quality LED products are increasingly available and emerging into the market.

On the other hand, there are many applications where the benefits of using LED products are not obvious. The use of LED tubes as replacement lamp is a typical product causing controversy because the impact on the lighting quality is often subordinate or ignored. Above, a lot of SSL products have an inferior quality and/or distributors provide confusing or inaccurate performance claims.

The performance of twelve LED tubes intended as replacements for T8 fluorescent lamps has been investigated. Bare lamp tests show low luminous flux values which could result in unacceptable low illumination levels, even though the luminaire efficiency may slightly increase when a fluorescent lamp is replaced by a LED counterpart. Furthermore, many LED tubes have inferior colour rendering properties and poor luminous maintenance characteristics.

This study shows that the power reduction associated with a one-to-one lamp replacement frequently results in an inadequate quantity and quality of illumination of the work plane. To maintain existing light levels, it would be necessary to install additional LED replacement lamps which decreases the potential energy savings. Furthermore, a luminaire with a LED replacement lamp has a considerably different luminous intensity distribution because the LED tube is a directional light source emitting light in a downward-hemispherical arrangement. This has an impact on the illumination distribution and uniformity.

In a psychophysical experiment, the performance of three currently available LED replacement lamps and a standard fluorescent T8 lamp in the same application was investigated in terms of general lighting quality, colour quality and glare perception. Although, this study indicates that a replacement of a single TL – in an existing luminaire – with a single LED tube could reduce the lighting quality in the room significantly, it is however not clear whether this would still be the case for an equal luminous output and a more uniform illuminance on the walls.

Anyway, customers must be aware of the characteristics of the LED replacement lamp and of the impact on the quantity and quality of the lighting.

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Appendix A. Power factor and *THD*: meaning and relationship

When a non-linear load is connected to the mains voltage, the current wave shape is non-sinusoidal (e.g. the current wave shape of a LED tube, Fig. 2). A non-sinusoidal periodic current wave shape (without a DC component) can be represented by a Fourier series of pure sinusoidal waves which contains the fundamental frequency ($n = 1$) and its multiples ($n > 1$), called harmonics:

$$i(t) = \sum_{n=1}^{\infty} \sqrt{2} \cdot I_n \cdot \sin(n\omega t + \alpha_n) \quad \text{(A1)}$$

With n = harmonic number, I_n = root mean square (*RMS*) of the n-th harmonic voltage component, ω = angular frequency in radions per second, t = time, α_n = the phase shift of the n-th harmonic voltage component.

The *RMS* of the non-sinusoidal current $i(t)$ is

$$I = \sqrt{\sum_{n=1}^{\infty} I_n^2} \quad \text{(A2)}$$

Harmonic distortion is the change in the waveform of the current or voltage from the ideal sinusoidal waveform. A measure for the distortion is the total harmonic distortion *THD*, which is defined as the ration of the root mean square of the harmonic content to the root mean square value of the fundamental quantity, expressed as a percent of the fundamental. The total harmonic distortion of the current is:

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \times 100\,(\%) \quad \text{(A3)}$$

For the voltage wave shape, analogue definitions can be defined. However, due to the low impedance of most power systems, the harmonic distortion of the supply voltage is mostly limited, even if there are significant amounts of harmonic current. Therefore, the mains voltage can be approximated as a pure sinusoidal wave shape in most applications.

The power factor λ is defined as the ratio of the real power input to the total volt–ampère (or apparent power) input to the load:

$$\lambda = \frac{P}{VI} \quad \text{(A4)}$$

In non-sinusoidal regime, the real power P can be written as

$$P = V_1 \cdot I_1 \quad \cos\varphi_1 + V_3 \cdot I_3 \quad \cos\varphi_3 + V_5 \cdot I_5 \quad \cos\varphi_5 + \cdots \quad \text{(A5)}$$

With φ_n the phase angle between the nth harmonic voltage component and nth harmonic current component. Under assumption of a sinusoidal voltage, the power factor λ becomes (Eqs. (A2) and (A5) in Eq. (A4)):

$$\lambda = \frac{P}{VI} = \frac{V_1 \cdot I_1 \quad \cos\varphi_1}{V_1 I} = \frac{V_1 \cdot I_1 \quad \cos\varphi_1}{V_1 \cdot \sqrt{I_1^2 + I_3^2 + I_5^2 + \cdots}}$$

$$= \frac{\cos\varphi_1}{\sqrt{1 + ((I_3^2 + I_5^2 + \cdots)/I_1^2)}} = \frac{\cos\varphi_1}{\sqrt{1 + THD_I^2}} \qquad \text{(A6)}$$

The power factor is a practical measure for the efficiency of the energy transport in power distribution systems. For two systems transmitting the same amount of real power, the system with the lower power factor will have a higher current value. Higher current causes higher losses in the distributions network.

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