California Energy Commission
Dockets Office, MS-4
RE: Docket No. 15-BSTD-01
Adoption of 15-Day Language for the 2016 Building Energy Efficiency Standards
1516 Ninth Street
Sacramento, CA 95814 5512
docket@energy.ca.gov

The California Energy Commission,

I write on behalf of my Company Once Innovations about the proposed Codes and Standards Enhancement Initiative (CASE) Residential Lighting (hereinafter the CASE Report) and the suggested "flicker" requirements on LED lighting technologies discussed on pg. 13 and Reference Joint Index JA10 pgs. 15-23. Once Innovations is a small company based out of Minnesota that sells LED lighting products. Once sells lights into the agricultural lighting market including into California. We are dedicated to making a more humane indoor lighting product for chicken, turkeys and swine with our patented spectrum based lighting. We also license our patented AC based LED technology for residential and commercial lighting including technology sold in California.

Implementing the standards on so called "flicker" provided in the CASE Report will eliminate choice for consumers of a less expensive LED lighting technology in the marketplace that has been widely accepted and adopted by consumers as an acceptable technology, resulting in the slowing in adoption of a much needed energy efficient technology. This will only act to increase problems associated with global warming. In opposite to the suggestions by the CASE Report, 100 and 120 Hz modulated LED lighting technology has never been shown in any study to cause any negative health results, including simple eye strain, and instead has been seen as acceptable in real-world situations. Any design requirement in addition to requiring 100 Hz modulation is unnecessary and will only act to increase product costs and thus decrease adoption of energy efficient LED technologies.[1] To this end Once requests California change the language of its proposed rules to present a requirement that LED technologies operate at or above 100 Hz or 120 Hz and additional modulation information be reported by manufacturers similar to that required by Energy Star or The European LED Quality Charter.

As background regarding LED lighting technologies, there are two main ways in the marketplace to operate a LED lighting device, the first is the traditional technology in the industry, which is to use an AC to DC converter (DC based). The second newer and typically less expensive technology is to modify AC without a DC converter (AC based). Companies that manufacture or sell these AC based lighting

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[1] The proposed additional requirements appear based upon current IEEE 1789 recommendations. Once has requested the IEEE Board investigate procedural flaws and the lack of AC LED representatives as balloting members for the recommendations that restrain trade against AC based lighting technologies and favor DC based lighting technologies.

products include Feit Electric, Seoul Semiconductor, Texas Instruments, Hubbell Lighting, Acuity Brand Lighting, Microchip, Exar, Edison Opto, American Bright, etc[2]. Based on the properties of these technologies, DC based LED lighting typically produces light without a frequency/modulation (0 Hz). AC based LED lighting in the marketplace produces light with a frequency/modulation of 100 Hz or 120 Hz.

While I understand that science can be mundane, tedious and legislatures would likely rather leave this to others, this decision has the potential to economically harm AC LED manufacturers and sellers based out of California and impede the adoption of energy efficient lighting that will cause harm to the environment. As a quick lesson in the properties of light, light has multiple properties including wavelength (measured in nanometers - nm), frequency/modulation (measured in Hertz - Hz), intensity (measured in lux), etc. Depending on these properties, different chemical reactions occur in humans. For example, light at a wavelength of 200nm will cause the chemical reaction of blindness, at 400 nm will cause the chemical reactions of causing a human to produce vitamin D and tan and at 600 nm will cause the chemical reaction of appearing orange. Similarly studies have shown for frequency/modulation at 30 Hz (full strobing light) in a portion of the population seizures will occur, at 70 Hz (more traditional flicker where some dark is detected) a portion of the population experiences headaches and at 120 Hz (existence of modulation typically not detected/perceivable in any form unless special condition present) and higher the evidence suggests with LED lighting no negative health effects and people find the lighting acceptable.

In the 1980s and 1990s fluorescent tube lighting existed that was shown to cause headaches among a small percentage of the population. Studies also showed reduced reading speed under fluorescent lighting, negative effects on cats, etc. Fluorescent lighting utilized a magnetic ballast that produced significant EMI (electromagnetic interference) and an unforgettable audible hum. It also operated at 100 Hz and 120 Hz frequencies. At the time some scientist concluded the 100 Hz and 120 Hz lighting frequencies where causing the negative health effects. However, since that time many tests have shown that EMI and audible noise such as that produced by the fluorescent tube lighting both cause headaches and can be responsible for the effects noted.

When AC LED lighting began being used in the marketplace at 120 Hz interest in these previous fluorescent lighting studies renewed. Additional testing has occurred. In 2013 Veitch, who had previously performed the test on 60 Hz fluorescent lighting that showed reduced reading speed released preliminary results of her study entitled Flicker Effects on Brain Activity. In this study frequencies of 0 Hz (DC), 100Hz and 500Hz were analyzed to determine the effect on sentence reading and Stroop tasks. In

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[2] This letter/comments by Once are solely provided by Once and the opinions and concerns outlined in this letter are in no way affiliated with or associated with the companies listed and Once is unaware of these companies' positions or opinions on the subject matter discussed. Listing them in no way should be seen as an endorsement, support or otherwise of Once's positions, instead this is merely a statement based on Once's knowledge of the marketplace.

the early results it showed "[T]he speed of reading sentences was the same regardless of the flicker condition."

Similarly a 120Hz fluorescent lighting study had been conducted on cats and noted phase-locked firing of LGN neurons in cats under the fluorescent lighting. Once manufactures lighting for poultry, animals with a significantly more complex and advanced visual system than humans or cats. In a study from the University of Delaware that has since published Once's 120Hz lights compared to CFL and a DC LED showed a Heterophils to lymphocyte (H:L) ratio was superior to that of CFL and DC LED lighting, indicating less stress on the bird. Not only does this show no health issues existed contradicting the previous fluorescent lighting study on cats, but the lights actually were beneficial and reduced stress, enhancing health and providing a more humane light source.

In Effects of Flicker Characteristics from Solid-State Lighting on Detection, Acceptability and Comfort, Bullough et. al Feb. 2011 multiple LEDs having multiple flicker index were provided to subjects at varying frequencies from 50 Hz to 300 Hz. Of the 9 different conditions in the trial 6 were done with 100Hz or 120Hz LED lighting devices.

Under each condition subjects indicated whether they could detect flicker in the following situations 1. When using a computer; 2. When looking at the luminaire; 3. When looking at point A (approximately 40° from the luminaire) 4. When shifting their gaze between point A and B in the room (separated by a visual angle of approximately 54°); 5. When waving their hand underneath the luminaire. In all with 10 test subjects, 6 conditions of 100Hz and 120Hz lighting and 5 different scenarios, 300 different modulation situations were considered. Then, if the subjects could detect a stroboscopic effect they were asked to provide the acceptability of the effect with -2 being very uncomfortable, -1 somewhat unacceptable, 0 neither acceptable or unacceptable, +1 somewhat acceptable and +2 very acceptable. Id. The end result, for each situation 1-5 for frequencies 100 Hz and above, in the few cases where modulation could actually be perceived the acceptability rating was over 1, or somewhat to very acceptable to subjects. In other words, 100% of participants in all 300 situations, real life or otherwise, showed no negative health issues and generally found lighting acceptable.

From the Bullough et. al. studies an additional paper was published - Detection and Acceptability of Stroboscopic Effects from Flicker. While this paper itself is not currently available to Once, Assist Recommends put out by the Lighting Research Center provided a paper entitled Flicker Parameters for Reducing Stroboscopic Effects from Solid-State Lighting Systems Volume 11, Issue 1 May 2012 providing additional analysis from the data presented in the second Bullough paper. In particular, an additional experiment was conducted where subjects provided acceptability ratings of detectable flicker on the same acceptability scale -2 – 2 when a light-colored rod was waved against a dark background. In this one situation in the 100 Hz to approximately 160 Hz range for percent flickers well above 25% and typically above 54% some ratings in the 0 to -1 acceptability range were provided.

Still, as indicated by the Assist paper:

> Because the study that assessed stroboscopic effects (Bullough et al. in press) used a light-colored, rapidly moving object viewed against a dark background, it comprises a near-worst-case condition for perception of stroboscopic effects. Slower movements, objects with lower contrast, and the presence of non-flickering light sources such as daylight would all be expected to reduce the likelihood of detecting, and to increase the acceptability of, stroboscopic effects from a flickering light source.

Thus, in nearly the worst conditions possible, with the worst performing lights, subjects found the flicker or stroboscopic effects of 100Hz and higher lighting to be somewhere between neither acceptable nor unacceptable to somewhat unacceptable. Basically some individuals were slightly annoyed with the extreme non-real world light colored wand waving.

Other studies on LED lighting operating at 100 Hz and higher typically involve some sort of special condition and whether under such special condition modulation can be perceived. However, no study reviewed shows that perception of modulating light from a LED device during a special condition results in a negative health condition such as a headache or even eye strain. In the only test where subjects were asked if the perceived modulation was acceptable in all real world situations the answer was yes. In sum, based on all studies on actual LED lighting devices operating at 100Hz and above show no health risks exist. In addition the tests on actual LED lighting devices further show in real world settings individuals find the light sources acceptable.

More significant to point out than the studies is that if actual health problems existed as a result of 120Hz LED lighting devices, this would be well documented by the public and industry. A significant portion of the LED lighting technology is now AC LED. Arguably around 20% of residential LED lighting devices are now AC LED and growing. Enough 120Hz AC lighting devices have been sold over the years that in the day and age of internet webpages, facebook pages, company webpages all dedicated to consumers voicing compliments or complaints that if a persistent health issue existed or even unacceptability, it would be well known in the field and adoption of AC technologies would not be increasing. Consumers have spoken and AC LEDs at 100Hz or greater are extremely acceptable in the marketplace with basically no health or headache issues being reported and instead AC LED products appear to be very acceptable to consumers just as the Bullough study indicates.

Most of the recommendations from the CASE Report appear to flow from IEEE 1789 committee recommendations. Once's CEO/CTO Zdenko Grajcar is a nuclear physicist who has extensively studied the effect on LED lighting on living organisms, including humans, avian, swine, and plants and has filed and received an abundance of patents in these areas including U.S. Pat. Nos. 8,651,691, 8,876,313 and 8,858,005 all entitled Light Sources Adapted to the Spectral Sensitivity of Diurnal Avians and Humans and has similar filings directed toward swine lighting, aquaculture lighting and horticulture lighting. Mr. Grajcar was a working group member for IEEE 1789 and recognized and complained of the bias within the working group and balloting members against manufacturers of AC LED technologies vs. DC LED technologies. The exclusion of AC LED manufacturer representatives in the balloting group underscores the procedural flaws that occurred during the IEEE 1789 standard making process. At this time Once is attempting to work with IEEE to determine why these procedural flaws occurred.

In reviewing the 2016 CASE Report, numerous errors exist regarding support for the proposed flicker requirements that appears to come from the IEEE 1789 committee. At page 17 last paragraph states "Flicker can be related headaches and eyestrain even when the light source is not perceived to flicker (Wikins et al. 1989). Wilkins compared the number of headaches . . . under two types of fluorescent lamp . . ." As indicated above, fluorescent lamps produced both EMI and audible noise that have been linked to headaches. No study exists on LED lighting where headaches were shown to increase or be caused from 100 Hz or 120 Hz lighting.

The first full paragraph of page 18 indicates in 1995 Veitch found visual performance was reduced under 60Hz AC fluorescent lamps compared to 20-60kHz lamps. As indicated above Veitch repeated this same test using 100 Hz LED lamps compared to 0 Hz LED lamps and the speed of reading sentences was seen as the same.

In the second full paragraph on page 18 indicates in the study by the Light Research Center and concludes "This region of frequencies and amplitude modulation is detectable by at least 80% of the population and the stroboscopic effects are considered very unacceptable." In Once's opinion this is just a complete misrepresentation. We believe this statement directed toward the Light Research Center are regarding the Bullough tests and Assist paper. Once is sending paper copies of these papers to be part of this record. Please read the Bullough test and the Assist paper on the second and decide for yourselves the accuracy of the suggestion that 80% of the population detected and found stroboscopic effects very unacceptable for 100 Hz and above LED lighting. 5 of 5 real-world situations at 100Hz and above all graded in the acceptable range even in the rare case when the stroboscopic effect was perceivable. The only situation where 100Hz or above was not "acceptable" and ranked between neither acceptable nor unacceptable to somewhat unacceptable was essentially the worst possible condition and a complete non-real world condition. Again, please read the actual papers and decide for yourselves the merits of this statement in the CASE Report.

Thus, of the three main studies the CASE Report uses to support the need for additional requirements above a minimum frequency of 100 Hz or 120 Hz the first is unsupported in relation to LED lighting devices, the second is contradicted by studies on LED lighting devices and the third is plainly misrepresentative of the LED light study that instead shows lighting at and above 100 Hz in real life situations is more than acceptable.

The most telling statistics from the CASE Report indicate that 15 out of 25 (60%) LED lighting devices tested failed the flicker test with 12% of the samples being lamps having less than 200Hz and amplitude modulation of 100%. The CASE Report suggests the market is not self-policing. The CASE Report seems to be missing the obvious – consumers are adopting devices in mass that fail these excessive requirements because the excessive requirements are completely unwarranted. The reason to police flicker is to ensure lamps that are unacceptable to consumers are not placed into the marketplace giving a bad name to all of LED lighting and reducing adoption. The problem here is that the lamps in the marketplace are acceptable to consumers as the Bullough test actually shows despite its inaccurate characterization by the CASE Report. As a result, the only thing the proposed flicker requirement will accomplish is forcing completely unneeded design changes on perfectly acceptable LED lighting devices thus unnecessarily increasing costs. Without question these increased costs will be seen as unacceptable to multiple consumers and thus reduce adoption of LED lighting technologies in favor of cheaper, less energy efficient lighting products. This undoubtedly will result in negative effects on the environment and economic harm to multiple California companies that sell AC LED products. Thus we request California adopt the same standard on flicker/modulation as Energy Star or The European LED Quality Charter and put an end to the "flicker" boogieman.

Sincerely

Joe

Joe Hoffmann

General Counsel
Once Innovations, Inc.

I. Evaluation of the impact of alternative light technology on male broiler chicken growth, feed conversion, and allometric characteristics[1]

Allison G. Rogers, Elizabeth M. Pritchett, Robert L. Alphin, Erin M. Brannick, and Eric R. Benson[2]

Department of Animal and Food Sciences, University of Delaware, Newark, DE

ABSTRACT This study evaluates the impact of light-emitting diode (LED), cold cathode fluorescent (CCFL), and incandescent lamps on broiler performance. Male Ross 708 broilers (n = 672) were raised to 6 wk age in 8 black-out modified large colony houses, under identical intermittent lighting conditions using 4 unique types of lamps, which were gradually dimmed throughout the study. Incandescent lamps served as the control; experimental technologies tested included CCFL and 2 different LED lamps. Each technology was tested in duplicate for each of 4 trials (8 replications total per technology) conducted across the course of one year to account for seasonal variance. Live performance for each technology was evaluated using live broiler body weight (BW), weight gain, feed conversion, and mortality. Birds were removed from each house at 7, 14, 35, and 42 d to be humanely euthanized, weighed, and necropsied for allometric tissue sample analysis. Relative to the technologies tested, results indicate that birds raised under incandescent lamps had significantly higher BW by 42 d, compared to birds raised under CCFL lamps, which had poorer BW performance ($P = 0.03$). Birds raised under both LED technologies grew to final BWs similar to those raised under incandescent light, with significant differences in neither feed conversion nor mortality.

Key words: broiler, LED, light, growth, performance

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INTRODUCTION

Changes in photoperiod and light intensity have brought about improvements in broiler chicken production; however, limited research is available to evaluate the impact of the type of light source birds are exposed to as they grow. In a study conducted by Mendes et al. (2013), utilizing 12 groups of 30 broiler chickens exposed to light-emitting diode (LED) and compact fluorescent lamps (CFL) in light-controlled pens, results indicated that birds grown under LED lighting generally exhibited improved production performance compared to those grown under CFL lamps during development. By day 40, however, there were significant differences in neither feed intake, live body weight (BW), nor feed conversion in both males and females. raised under either LED or CFL (Mendes et al., 2013). This is an incentive to evaluate the effect of a variety of alternative lighting technologies on broiler growth and performance throughout the birds' development, with a focus on the final live BW and feed conversion ratio obtained by the broilers, as this is of economic concern to broiler producers and growers.

Recently, light technology has been of interest to the agriculture industry given the advancement of alternative, high-efficiency lamps. Standard incandescent lamps, which consist of a heated filament within a bulb, have a short working life, and convert only 5% of the energy they draw into usable light, wasting the remaining energy as heat (Matsumoto and Tomita, 2010). Alternative technologies that have been utilized in the field, including LEDs and fluorescent lamps. LED lamps are compound semiconductor devices that release electrical energy as photons, producing different colors based on the energy state of the photons (Jacob, 2009). Cold cathode fluorescent lamps (CCFLs) apply a high voltage to an electrode, which causes mercury within the bulb to become excited and emit ultraviolet light. The ultraviolet light is then converted to visible light by a phosphor coating on the inside of the bulb (Alberts et al., 2010). Of the various technologies, LED lamps have the advantage of requiring neither preheating nor startup time, and are favored as a more sustainable light source because they do not contain mercury (Rea, 2010). Each of these technologies contrasts sharply with the natural light under which the broilers' ancestors would have lived in that they emit narrow, distinct ranges of the visible light spectrum (Prescott and Wathes, 1999; E.R. Benson, unpublished research). Natural light, on the other hand, displays a very broad,

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[2]Corresponding author: ebenson@udel.edu

uniform distribution of power over the visible light spectrum, as well as into the ultraviolet and infrared range (Prescott and Wathes, 1999). The uneven distribution of wavelength in artificial lighting undoubtedly has an effect on avian behavior and physiology; however, little is known about how chickens perceive and respond to these different light sources.

Domestic chickens have highly sensitive, complex eyes and photoreception systems. Light enters the avian eye and activates the retinal sensory tissue at the back of the eye. The light is absorbed by photopigments, such as rhodopsin and iodopsin, in the retina where it is then converted and transmitted to the optic lobes of the brain as electrical signals by the optic nerve (Lewis and Morris, 2006). Chickens are capable of seeing a wide range of the light spectrum, including ultraviolet light, with the use of several visual receptors including rods, cones, and oil droplets which are thought to enhance vision (Meyer, 1986). These mechanisms allow the birds to have a high spectral sensitivity in comparison to humans. Poultry, like humans, are most sensitive to green light (520 to 580 nm) wavelengths; however, birds are more sensitive to blue light (460 to 500 nm) and yellow-orange-red light (620 to 680 nm) than humans. Increased light sensitivity results in poultry perceiving light from some sources more intensely than humans and may result in behavioral and physiological responses to varied lighting conditions (Meyer, 1986; Saunders et al., 2008).

The objective of this study was to examine the performance effects of LED and CCFL light technologies on commercial broiler chickens as compared to standard incandescent lighting. Live performance parameters were used to quantify differences between each technology.

MATERIALS AND METHODS

Male Ross 708 broiler chickens (n = 672) were obtained and raised from day zero to market age (42 d) in 8 large colony houses, following standard husbandry procedures outlined by the Agricultural Animal Care and Use Committee (AACUC) on the University of Delaware Farm [(33) 04-17-12R]. Each large colony house was blackout modified, and one of the 4 light technologies was installed throughout each house to serve as an experimental treatment, as described below. Birds (n = 84) were placed into each colony house under intermittent lighting programs (2 h light/4 h dark). Conditions in each large colony house differed only by lighting technology during the trial. This procedure was replicated 4 times over the course of one year to account for seasonal variance.

Technologies Implemented

Four lighting technologies were tested in this experiment: one brand of standard incandescent bulb (75 W Sylvania, Danvers, MA), 2 brands of LED lamps referred to as LED A and LED B for this study (LED A-10 W Next Gen, Fayetteville, AR; LED B -12 W ONCE AgriShift PLWB, Plymouth, MN), and one brand of CCFL (8 W Litetronics Microbrite, Alsip, IL). As the current industry standard, the incandescent bulb served as the control technology, while CCFL and LED lamps served as the experimental technologies. Each of the 4 light technologies was placed throughout 2 houses for a total of 8 houses/trial. Between seasonal trials, the light technologies were rotated through the large colony houses prior to the start of a new trial to account for house effects.

Light Intensity and Duration

The lamps were integrated with electronic controller (Chore-Time, Model 8, Milford, IN) and dimmer (Precision Lighting System 7200 MR3, Hot Springs, AR) systems to control the photoperiod, light intensity, and temperature in each house. An intermittent lighting program was used to allow the birds to fully feed during the light period, and for the birds' crops to empty completely during the dark period (Barott and Pringle, 1951). The lighting program was standardized across houses, with a program of 24 h light to 0 h dark (24L:0D) for the first 2 days, changing to 23L:1D at day 3. At day 7, bird acclimation to an intermittent lighting schedule began with a change to a cycling of 5.45 h light and 15 min dark. Between days 7 and 22, photoperiod was reduced by 15 min each day until a schedule of 2L:4D was achieved; this setting was then maintained to completion of the trial. Luminance in each house began at 43 lux (LX), equivalent to 4 foot candles (FCs), and was reduced to 11.1 LX (1 FC) at day 7. Luminance was further reduced to 8.9 LX (0.8 FC) at day 15, and was gradually lowered to 6.7 LX (0.6 FC) at day 16, 4.4 LX (0.4 FC) at day 17, and 2.2 LX (0.2 FC) at day 20. A final luminance of 1.1 LX (0.1 FC) was maintained from days 21 to 42. The luminance was adjusted and measured using a light meter (Sper Scientific, Model 840020, Scottsdale, AZ). Air temperature, relative humidity, and illumination were monitored at 15 min intervals using Hobo U12 data loggers (Onset Computer Corporation, Bourne, MA). This data was downloaded weekly and exported to Excel to track house conditions.

Broiler Care and Feed Monitoring

The broilers were raised in 2.29 × 3.35 m (7.5 × 11 ft) pens within each large colony house to reach the industry standard stocking density of 0.07 m^2/broiler (0.75 ft^2/broiler) at 42 days. and feed and water were provided ad libitum. Birds were fed commercial broiler starter feed [Crude protein (CP), 22%; crude fat, 3.5%] for days 1 to 21, and then commercial broiler finisher feed (CP, 18%; crude fat, 4%) for days 22 to 42

(Southern States Cooperative, Richmond, VA). Mortality was recorded daily, as was the weight of each deceased bird, to increase the accuracy of the feed conversion ratios. Feed consumption was measured (in kilograms) using a hanging scale (Rubbermaid Pelouze 7750, Winchester, VA) to weigh both the feed remaining each day and the amount of new feed added.

Randomly selected broilers (n = 6) were weighed each week to monitor growth and obtain representative weights to estimate weekly feed conversion. The remaining 480 birds were kept throughout the trial to collect additional live performance data. Cumulative feed conversion (CFC) from each house was calculated using Equation (1)

$$CFC = \frac{total\,feed\,wt.}{(total\,wt.\,birds\,remaining + mortality\,wt. + necropsy\,wt. - initial\,wt.\,of\,placed\,chicks)} \quad (1)$$

Live Performance and Allometric Characteristics

Randomly selected birds (n = 6) were removed and humanely euthanized by cervical dislocation from each house at days 7, 14, 35, and 42, to evaluate live performance and allometric growth characteristics. Live performance was measured by recording the live weight of the birds. The weight of the entire left breast muscle (pectoralis major and minor), heart, liver, and duodenal loop, along with the length of the duodenal loop were collected to compare allometric growth.

Statistical Analysis

Tests conducted include ANOVA, Fit Model, and Student's *t*-test using the statistical software JMP Pro (Version 10.0, Cary, NC). All statistical analysis was conducted at the 5% significance level ($\alpha = 0.05$).

RESULTS

Effect of Light Technology on Undressed Market-Age Weight

BW mean values for the experimental technologies were compared to the control mean under incandescent lamps (Figure 1). Day 42 BW did not differ significantly between incandescent, LED A, and LED B. However, BW under CCFL lamps were significantly lower than body weights under incandescent ($P = 0.03$).

Effect of Light Technology on Average Weekly BW Gain

Average weekly BW gain was calculated for each technology for 3 trials and averaged to observe growth trends. No significant difference was observed among technologies at each week (Figure 2).

Effect of Light Technology on CFC Ratio

No significant difference was detected in CFC across light technologies (Figure 3). LED B showed a lower CFC, and CCFL showed a higher average CFC. However, the difference between CCFL and incandescent is insignificant ($P = 0.3$), as is the difference between LED A and incandescent ($P = 0.18$). Likewise, there was no significant difference between LED B and CCFL ($P = 0.24$) or between LED technologies ($P = 0.14$).

Impact of Season on Market Age BW and CFC Ratio

Due to differences in BW performance observed during each trial, a statistical analysis of mean market age (42 d). BW and CFC ratios was performed by trial (season) and technology (Table 1). Mean broiler BW under CCFL were significantly lower during trial 2 (fall) than under all other trials ($P \leq 0.0002$). Mean BW under LED A were significantly lower as well during Trial 2 (fall) as compared with trial 3 (spring) ($P = 0.04$). No other significant differences were detected in feed conversion ratios among the remaining trials under all technologies.

Effect of Light Technology on Whole Breast Muscle Weight

No significant difference was observed between light technologies with respect to whole breast muscle weight; however, it was noted that the breast muscle weights proportionately paralleled mean BW. Breasts from birds raised under incandescent lamps were the heaviest on average, and those from CCFL-raised birds were the lightest.

Effect of Light Technology on Broiler Mortality

No significant difference in mortality was found across technologies (Figure 4). Mortality was calculated by flock by dividing the number of dead and culled broilers by the total number of birds raised under the technology in both houses, and converted to a percentage for ease of comparison. No difference in mortality was observed between CCFL and incandescent

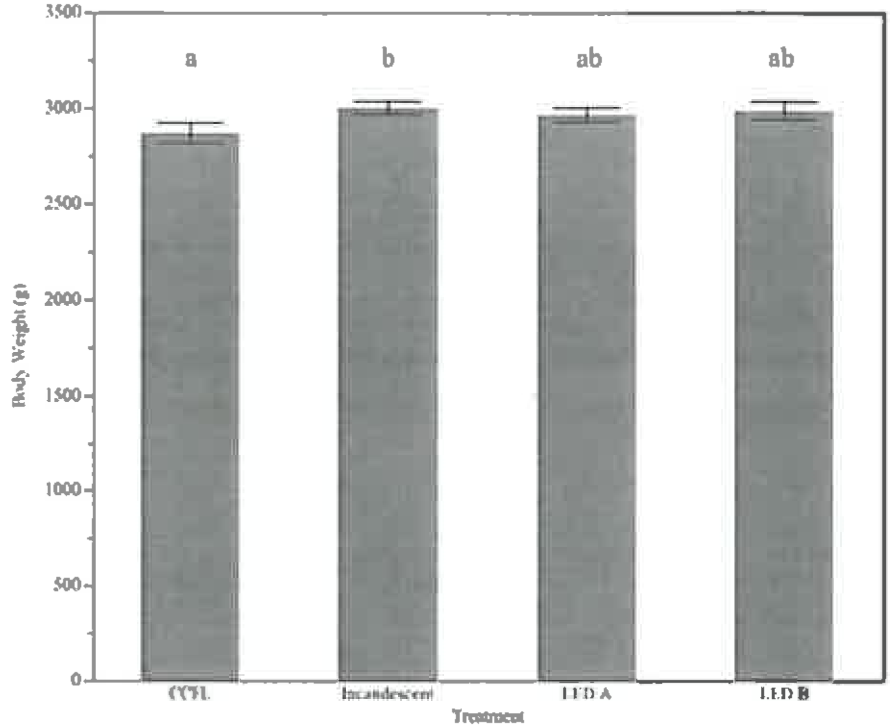

Figure 1. Mean BW in grams of adult male Ross 708 broilers, 42-days-old, arranged by lighting technology. Error bars represent SEM (CCFL, n = 49; incandescent, n = 48; LED A, n = 47; and LED B, n = 48). Letters denote statistical significance between treatments.

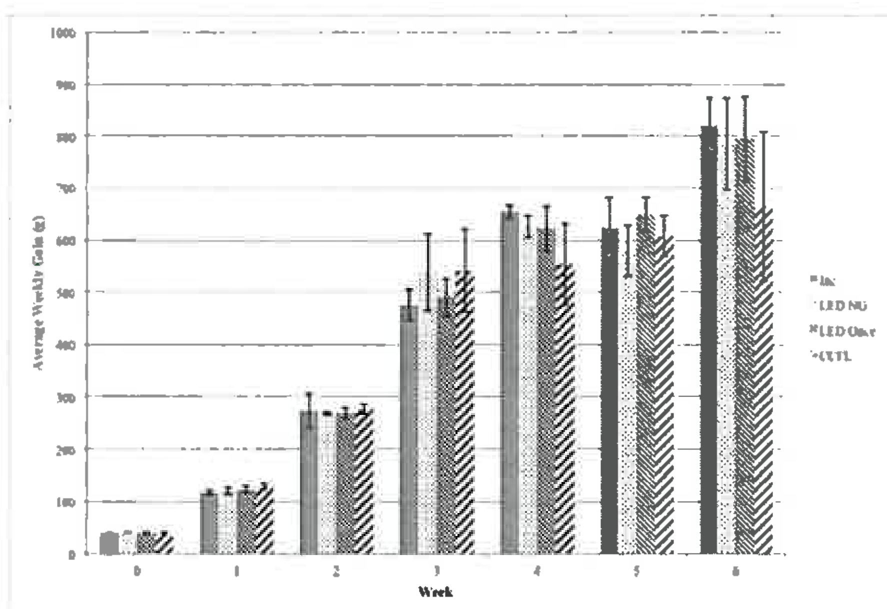

Figure 2. Average weekly BW gain in grams of male Ross 708 broilers under each technology arranged by trail. Error bars represent SEM (CCFL, n = 49; incandescent, n = 48; LED A, n = 47; and LED B, n = 48).

lamps ($P = 0.50$). The greatest disparity in technology, although still not significant, is between CCFL and LED B ($P = 0.33$) with birds raised under CCFL experiencing less mortality on average than those raised under LED B.

Additional Allometric Analysis

Additional allometric analysis was conducted on tissues collected from the euthanized broilers in this study for further insight into organ development. No

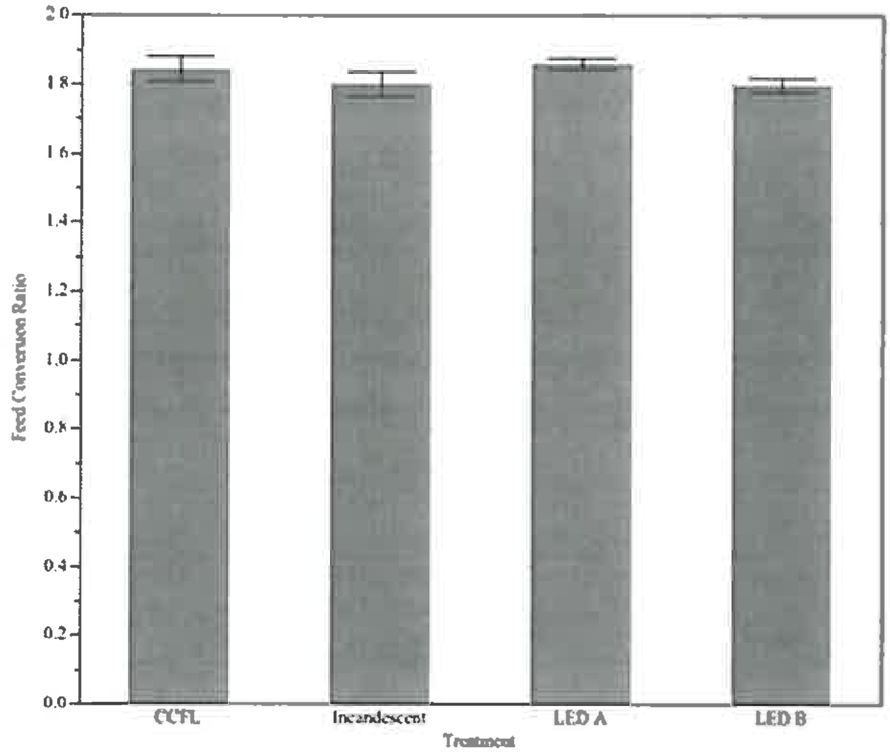

Figure 3. Mean CFC ratio of adult male Ross 708 broilers (kilograms feed per kilograms birds). Error bars represent SEM (CCFL, n = 8, incandescent, n = 7; LED A, n = 7; and LED B, n = 8).

significant differences were witnessed in the duodenal length, or mass of the birds' hearts, livers, and duodenums under any technology tested. Organ characteristics were additionally normalized to individual bird BW and were not found to be significantly different between treatments.

Table 1. Mean BW and CFC ratio of male Ross 708 broiler chickens, 42-days-old, for the light treatments incandescent, LED A, LED B, and CCFL during trials 1 to 4. Data presented as mean ± SEM. Trial 1, summer; trial 2, fall; trial 3, winter; and trial 4, spring.

Treatment	Trial	Mean BW (g)	Feed conversion ratio (kg)
Incandescent	1	3,031 ± 64[1]	1.75 ± 0.0
	2	2,915 ± 93[1]	1.81 ± 0.09
	3	3,097 ± 51[1]	1.87 ± 0.05
	4	2,958 ± 41[1]	1.75 ± 0.09
	Mean	3,000 ± 33	1.80 ± 0.04
LED A	1	3,007 ± 68[1,2]	1.90 ± 0.0
	2	2,877 ± 62[1,2]	1.81 ± 0.004
	3	3,091 ± 69[2]	1.87 ± 0.03
	4	2,901 ± 85[1,2]	1.88 ± 0.004
	Mean	2,966 ± 37	1.86 ± 0.02
LED B	1	2,986 ± 64[1]	1.82 ± 0.04
	2	2,953 ± 92[1]	1.77 ± 0.006
	3	3,062 ± 73[1]	1.82 ± 0.002
	4	2,941 ± 134[1]	1.78 ± 0.09
	Mean	2,986 ± 46	1.80 ± 0.02
CCFL	1	3,038 ± 76[1]	1.83 ± 0.004
	2	2,487 ± 58[2]	1.89 ± 0.08
	3	2,971 ± 123[1]	1.89 ± 0.02
	4	2,979 ± 64[1]	1.76 ± 0.14
	Mean	2,871 ± 53	1.84 ± 0.04

[1,2]Means within the same column without a common superscript differ ($P < 0.05$).

Analysis of Environmental Variables

A summary of fit was conducted at $\alpha = 0.05$ and $\alpha = 0.1$ to determine the impact of each trial (season), house, and experimental technology on the market age weight of the birds using JMP Pro 10. An R^2 value of 0.18 was obtained, indicating that the majority of the variability seen in our data is due to random error, which can most likely be tied back to individual differences between each bird; in conducting an effect test, trial number (or season) was found to be significant at $\alpha = 0.05$ ($P > 0.0001$), and experimental technology was found to be significant at the $\alpha = 0.1$ level ($P > 0.09$). Effect of house was insignificant at both $\alpha = 0.05$ and $\alpha = 0.1$.

DISCUSSION

The objective of this study was to examine the effect of incandescent, LED, and CCFL technologies on broiler performance. Converse to the hypothesis that no differences would be observed in performance across technologies (incandescent, LED A, LED B, and CCFL), lighting technology significantly impacted the 42 day BW of the broilers in this study, with CCFL lamps resulting in lower average BW. CCFL lamps, however, resulted in significantly lower BW on

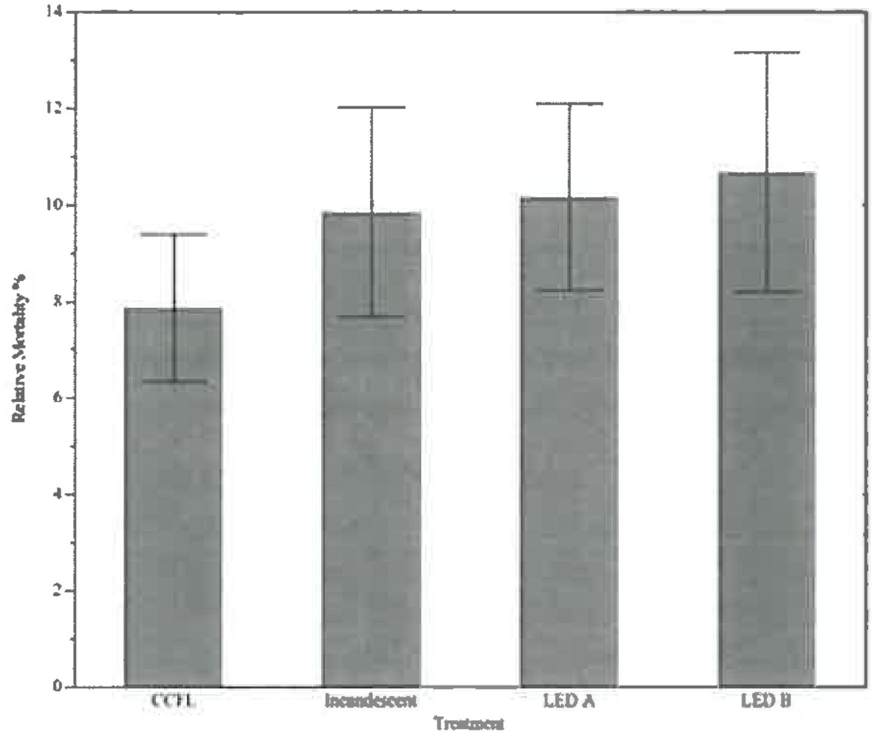

Figure 4. Mean experimental percentage of mortality of male Ross 708 broilers by technology. Error bars represent SEM (CCFL, n = 8; Incandescent, n = 7; LED A, n = 7; and LED B, n = 8).

average than the control, with a difference of about 130 g observed on average between incandescent and CCFL lamps. On the other hand, the 2 LED technologies performed similarly to the control incandescent lamps, which could support implementation of LED lighting in broiler houses in the future.

As compared to male Ross 708 performance standards normalized for live BW, deboned breast muscle weights obtained during this study were found to be lower on average (Aviagen, 2012). This disparity between the Ross standards and the average weights from the experimental subjects is likely due to human inaccuracy (during removal of the pectoralis major and minor from the keel bone), as trained volunteers rather than professional production workers collected specimens. More importantly, however, the mass of the breast muscle under each technology correlated with the mass of the birds in this study at market age. Thus, birds raised under CCFL lamps had lower breast muscle weights on average than birds raised under the control or either of the 2 LED technologies.

In this study, it was determined that season had a significant impact on performance, but house placement did not. A seasonal difference in performance of broilers throughout the year is well-supported both in the literature and anecdotally (Sinclair et al., 1990). In this study, it was not possible to control for all variables, such as potential differences in breeder flocks. Thus, variance in BW might have been due to breeder flock differences between trials; however, these differences were likely amplified by the technology under which the birds were raised during each trial.

It is unclear at this time what lamp attributes could be causing the differences in BW, and to a lesser degree in breast weight, between the CCFL lamps and the control incandescent lamps. One possibility is that the differences in the light output spectrum for CCFL versus the incandescent and LED lamps used in this study may affect the broilers' growth, even after light intensity is decreased with age, as is the normal for broiler management. For instance, Prayitno et al. (1997) found that broilers raised under red light early in growth showed increased BW compared with those raised under blue light during the same time period, suggesting that the wavelength of light plays a critical role in growth. In contrast, studies carried out by Rozenboim et al. (2004) and Cao et al. (2012) indicated that a significantly higher final BW in broilers was achieved with monochromatic green LED light early in growth followed by a switch to monochromatic blue light, as opposed to a conventional white light program. An additional study conducted by Baxter et al. (2014) found that Smoky Joe Leghorn laying hens raised under monochromatic green LED lighting, as compared to monochromatic red or white LED lighting, showed increased growth from 23 to 52 wk age. A significant difference between Baxter et al. (2014) and this study is that the other study worked with laying hens, and these birds experienced different physiological stressors including egg production, leading the authors to conclude that this increase in BW may have been due to a correlating decrease in egg production. Further studies utilizing a spectrophotometer to characterize the spectral power distribution of different lighting technologies used in this study are underway. Additional research on the effect of light wavelength on broiler growth, health, genetics, and behavior is needed to further understand poultry's interaction with their environmental light source. The impact of lighting technology on bird stress was considered in a parallel investigation to production parameters, and is provided in part 2 of this study.

This study provides evidence that not all lamp technologies may be suitable for implementation in commercial broiler chicken houses. Although there was little difference observed in production parameters between the 2 LED technologies and standard incandescent lamps, the CCFL lamp used in this study may have contributed to lower final BW2 in the birds raised under this technology. Thus, LED technology may be installed as a high-efficiency alternative to incandescent lighting, whereas CCFL may not, when considering cost savings in energy consumption for broiler growers while maintaining bird profit.

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Flicker Effects on Brain Activity

The emergence of solid-state lighting turns attention back to flicker

BY JENNIFER A. VEITCH

In the "bad old days" (25 and more years ago), most commercial and institutional interior lighting consisted of fluorescent lamps run on magnetic ballasts. This light source had an inherent flicker rate of 120 Hz in North America, where the mains AC supply operates at 60 Hz. There were variations in the amplitude of this flicker depending on the lamp type, but it was on the order of 17–40 percent[1]. Laboratory research found that these flicker conditions could disrupt saccadic eye movements[2], reduce visual performance[3] and reduce clerical work performance[4], always in comparison to fluorescent lamps operated on high-frequency electronic ballasts. A field investigation found that the incidence of headaches and eye-strain was lower when electronic ballasts were in use than when magnetic ones operated[5]. When electronic ballasts came into widespread use in the mid- to late-1990s, partly in response to energy-efficiency legislation, I and many other researchers turned to other topics. With most office lighting operating at >20 kHz, there seemed little reason to continue to study flicker.

That is, until solid-state lighting (SSL), and in particular light-emitting diodes (LEDs), came along. As with a fluorescent lamp, an LED requires a device (known as a driver) to modulate the current delivered to the diode. Unlike the binary choice between magnetic and electronic ballasts for fluorescent systems, there is no intrinsic flicker pattern associated with LED lighting[6], and currently-available products exhibit a wide variety of flicker patterns[7]. Knowing the history of research based on fluorescent lighting systems, a perceptive electrical engineer from Northeastern University, Prof. Brad Lehman, initiated a committee within IEEE to study the problem and to make recommendations for current modulation that would mitigate any possible harmful effects (IEEE PAR 1789, *http://grouper.ieee.org/groups/1789*). That committee is currently drafting its preliminary recommendations.

Involvement in that committee led my colleagues and me to begin again to study the effects of invisible, imperceptible flicker on viewers. What we know about the effects of flicker on reading, cognitive performance and brain activity primarily comes from comparisons between 100 or 120 Hz fluorescent lamps on magnetic ballasts and 20–40 kHz fluorescent lamps on electronic ballasts. This generally showed that outcomes were poorer with lighting at the lower frequency flicker, but precisely why that might be the case was unknown. Little was known about the effects of flicker between these extremes. Previously, it was difficult to generate other flicker frequencies for experimental purposes and there was little practical reason to do so. Now, given the freedom available to electronics engineers to design LED drivers with almost any operating properties, this knowledge could be put to practical purpose.

COLLABORATIVE EFFORT

We formed a multi-disciplinary, multi-institution team to conduct this work, a collaboration between NRC (Dr. Jennifer Veitch, Greg Burns and Dr. Erhan Dikel), Carleton University (Dr. Amedeo D'Angiulli and Patricia Van Roon), the University of Essex (Prof. Arnold Wilkins), and Northeastern University (Prof. Brad Lehman). The work was financially supported by the National Research Council of Canada, the Clean Energy Fund (managed by Natural Resources Canada), OSRAM Sylvania, the J.H. McClung Lighting Research Foundation and Carleton University.

For our first experiment, we decided on a straightforward comparison of three flicker frequencies: 0 Hz (DC), 100 Hz and 500 Hz, all with a square wave, 100 percent modulation, and a 50 percent duty cycle (**Figure 1**). By varying the number of chips and the voltage delivered, the system delivered a steady ~500 lx on the horizontal surface of the viewing booth regardless of the flicker condition. Based on the literature, we expected that 100 Hz flicker would cause problems in comparison to both 0 Hz and 500 Hz. The existing evidence suggested to us that low-frequency invisible flicker would disrupt eye movements (as compared to no flicker at all) and that it might cause irrelevant brain activity that would reduce cognitive performance. It seemed likely to us that 500 Hz would be a sufficiently high rate that the neural system would not be able to detect it; the highest rate at which flicker had been previously detected (at that time) was ~200 Hz. We chose 100 Hz rather than 120 Hz to ensure that we could distinguish this from any measurement artifacts related to the mains frequency.

Participants looked at a computer monitor in the booth that we had modified to use our LEDs as the light source, operating in sync with the overhead LEDs in the booth (**Figure 2**). We determined empirically that there was no visible "beat" between the (75 Hz) refresh rate of the monitor and any of the experimental conditions.

Our experiment differed from others in using two measures of cognitive performance: sentence reading speed and Stroop task performance. The Stroop task requires the individual to respond to either the meaning of the presented word (RED, GREEN, YELLOW, BLUE) or the color in which it appears (red, green, yellow, blue) (**Figure 3**). Regardless of whether the task is to identify the color or the word, it takes more effort to respond when the color and word are incongruent (e.g., RED is shown in green text). Based on the previous research, we expected this increased effort to be even larger under 100 Hz than at either 0 or 500 Hz. The extra effort could be manifested as either slower responding or lower accuracy for incongruent trials as compared to congruent ones.

During these tasks, we also recorded eye movements and brain activity. We used electro-encephalography (EEG) to study visual event-related potentials, which in this case means that we are examining the amplitude of brain activity that happens in the period immediately following a stimulus, such as the onset of the word in the Stroop task. The 68-channel EEG system also allowed us to examine the brain locations where activity was greatest.

EARLY RESULTS

The data analysis is underway now, and the results thus far are very interesting. The speed of reading sentences was the same regardless of the flicker condition. Measured using response time, the extra cognitive effort for an incongruent trial in the Stroop task was also the same regardless of flicker condition (i.e., there were no statistically significant differences). However, we also have a performance accuracy measure for the Stroop task. For all the conditions,

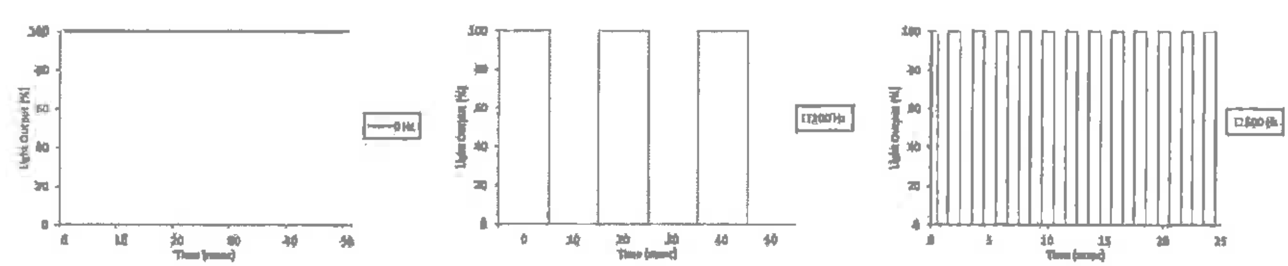

Figure 1. For the 0 Hz condition (left panel) light output was steady at 100%. For 100 Hz (center panel), light output varied between 0 and 100% 100 times per second with an equal time in the off and on state (50% duty cycle). For 500 Hz (right panel), light output varied between 0 and 100% 500 times per second with an equal time in the off and on state (50% duty cycle).

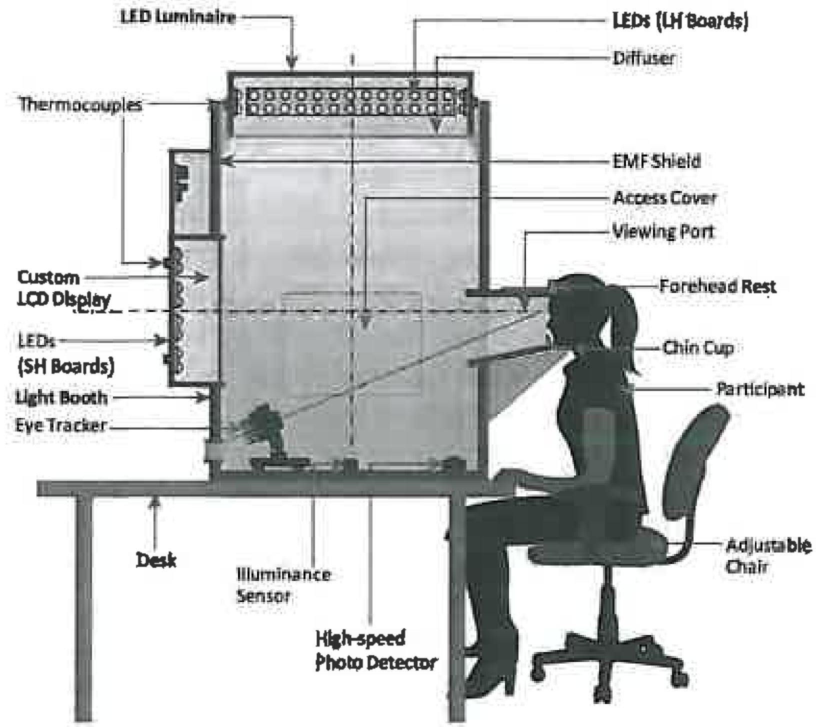

Figure 2. The participant looked at questionnaires and tasks on a vertically-mounted monitor in a custom booth, with all light sources controlled together.

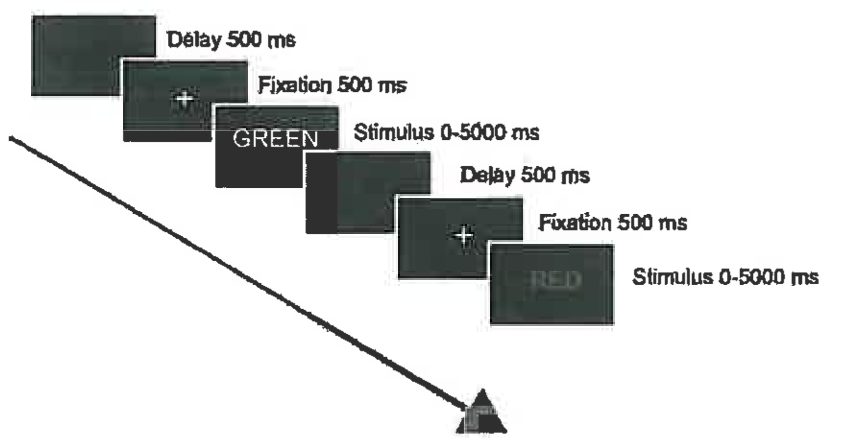

Figure 3. The task sequence for two trials of the Stroop task. Participants pressed a button indicating either the color of the word or its meaning, depending on the instruction. The first trial shown here is incongruent, and the second is congruent.

performance accuracy was lower for incongruent than congruent trials (as expected), but this was not uniform across the flicker conditions. This measure showed that there was less cognitive effort for an incongruent Stroop trial under 500 Hz flicker than under 100 Hz flicker (**Figure 4**), with a moderately large, statistically-significant effect ($F(1,31) = 9.57$, $p<.01$, $\eta^2 partial = 0.24$). This is as we had predicted. What we had not predicted was that the cognitive effort effect would be the same under 0 Hz and 100 Hz operation (that is, that processing an incongruent color-word pair would be equally difficult under 0 Hz and 100 Hz). We will need to examine this effect in more detail; in any experiment, there are many ways to fail to find an effect because of problems with the experiment. However, these findings also have precedent in the neuroscience literature, where there are suggestions that noise in the system might improve cognitive processing under some conditions[8].

We also have more work to do with these data. We have still to finalize the EEG analyses to look at the amplitude of responding to the onset of the stimuli. By conducting a fast-Fourier transform on the EEG recordings, we can also do the more traditional examination of the relative distribution of brain activity by wavebands (alpha, beta, delta, gamma or theta activity). The analyses of blinks and saccadic eye movements during the reading and Stroop tasks should, we expect, show disruptions during 100 Hz that replicate previous findings. Stay tuned for more information.

When we have completed the suite of analyses for this experiment, we will have added an important piece to the consideration of how LEDs ought to be operated, but clearly we will not have answered all the

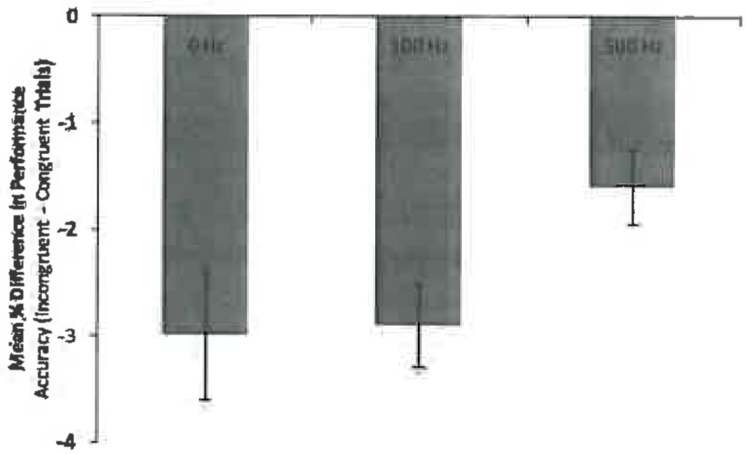

Figure 4. Cognitive effort was greater for the 0 Hz and 100 Hz conditions than for the 500 Hz condition, as seen in the larger drop in performance accuracy for incongruent trials compared to congruent ones. The chart shows means with the standard error of the mean.

questions. Whereas the debate at present has focused on preventing adverse effects, another look at the information might lead us to the aim of creating favorable conditions for cognitive work. This needs to be approached very carefully, particularly given the evidence of differences in sensitivity to flicker and its role, for some people, as a trigger for headache and migraine. We need to understand the role of this cyclic variation in light output on many behavioral and physiological outcomes in order to make good decisions about the operating properties of light sources, both those in development today and any that may come in future. ■

THE AUTHOR

Jennifer A. Veitch, Ph.D., Fellow IES (Member 1988), is a senior research officer at the National Research Council Canada (NRC). She's best known for her research on lighting quality, individual controls, and environmental and job satisfaction in open-plan offices. She is active in several professional associations and committees, including IEEE PAR1789. She serves on the IES Lighting Criteria Committee and is an associate editor of *LEUKOS*.

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ASSIST *recommends...*

Flicker Parameters for Reducing Stroboscopic Effects from Solid-state Lighting Systems

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Lighting Research Center

Rensselaer

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Lighting Research Center Technical Staff

J. D. Bullough, K. Sweater Hickcox, T. Klein, A. Lok, N. Narendran

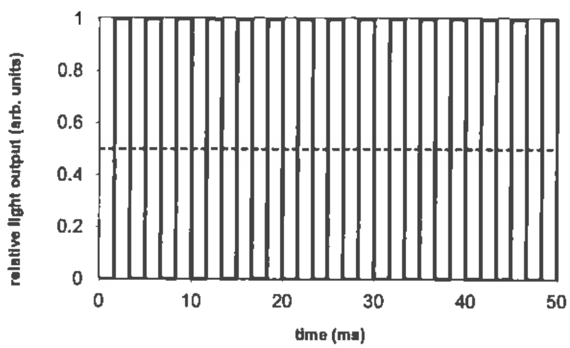
Contents

Introduction

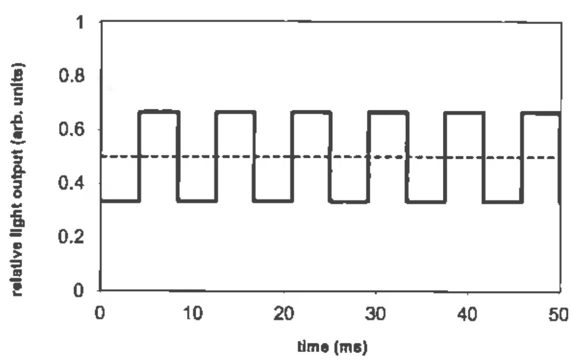
Nearly all lighting systems produce flicker, defined in this *ASSIST recommends* as the rapid fluctuation of light output in a cyclical manner. For many conventional lighting technologies (e.g., incandescent, fluorescent, and high intensity discharge [HID] lamps), flicker is a consequence of 60 Hz (largely in the Americas) and 50 Hz (in Europe, Asia, Africa and Australia) alternating current (AC) power line frequencies. Alternating polarity at these frequencies can result in flicker at twice the power line frequency (e.g., 120 Hz or 100 Hz), if electronic ballast circuitry is not employed. The thermal mass of incandescent filaments and decay characteristics of phosphors can reduce the flicker amplitude. This amplitude can be characterized in different ways (Rea 2000), the most commonly used of which are *percent flicker* and *flicker index*. Percent flicker is defined in terms of the difference between the minimum and maximum light output during a flicker waveform cycle:

$$\text{Percent flicker} = [(\text{maximum} - \text{minimum})/(\text{maximum} + \text{minimum})] \times 100\%$$

Figure 1 illustrates two rectangular waveforms showing the temporal modulation of light output as a function of time. The waveform in Figure 1a shows 100% flicker at 300 Hz, while the waveform in Figure 1b shows 33% flicker at 120 Hz.



a.



b.

Figure 1. a) Flicker waveform showing 100% flicker at a frequency of 300 Hz; b) flicker waveform showing 33% flicker at a frequency of 120 Hz.

If a light source ever produces no light during any portion of the cycle (as in Figure 1a), the percent flicker is 100%. Flicker index (Eastman and Campbell 1952) is defined with respect to a plot of the light output curve as a function of time (Rea 2000). Flicker index is the area under the light output curve and above the time-averaged light output for the entire cycle, divided by the total area under the light output curve. For a given waveform shape and duty cycle (duty cycle is defined here as the percentage of time during a flicker cycle that the light output exceeds 10% of the maximum value), percent flicker and flicker index are proportional to each other.

Direct visual perception of flicker is negligible at frequencies of 100 Hz or higher (Kelly 1961, De Lange 1958, Bullough et al. 2011). However, indirect perception of flicker is possible through stroboscopic effects at frequencies of 100–120 Hz (Rea and Ouellette 1988) and widespread perception of stroboscopic effects has been reported at 500 Hz (Hershberger et al. 1998). The variety of methods by which light-emitting diodes (LEDs) can be driven means that various flicker frequencies and percent flicker values could be possible in lighting systems using these sources. Perception of stroboscopic effects decreases as frequency increases (Hershberger et al. 1998, Bullough et al. 2011) and as percent flicker (or flicker index) decreases (Rea and Ouellette 1988). This *ASSIST recommends* document outlines a preliminary method for trading off these two factors based on recent data (Bullough et al. in press). This method does not include non-visual effects of flicker such as eyestrain or headaches (IEEE 2010).

Detection of Stroboscopic Effects

For rectangular waveforms operated so that the maximum light output is produced 50% of the time and the minimum light output is produced 50% of the time, the percent likelihood of detection (d, in percent) of stroboscopic effects can be estimated in terms of the frequency (f, in Hz) and percent flicker (p, in percent) as follows (Bullough et al. in press):

$$d = [(25p + 140)/(f + 25p + 140)] \times 100\%$$

The detection data from the study by Bullough et al. (in press) are shown in the contour plot in Figure 2, as a function of flicker frequency and percent flicker. Also shown in Figure 2 are the frequency and percent flicker values for several common light sources.

This equation is applicable to frequencies from 100 to 10,000 Hz and for percent flicker values from 5% to 100%. The visual task used to assess stroboscopic effects was waving a light-colored rod against a dark background (Bullough et al. in press), and represents close to a worst-case scenario for detection of stroboscopic effects.

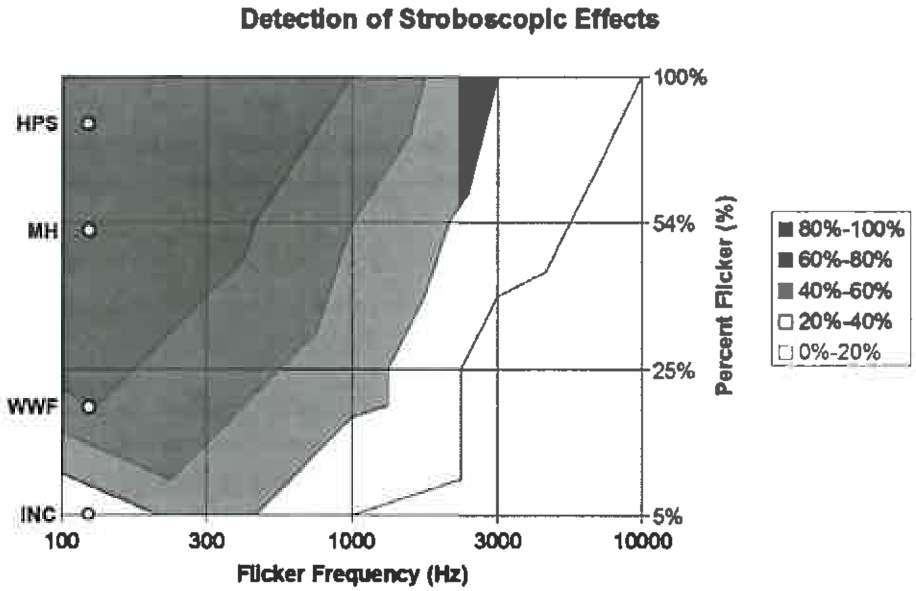


Figure 2. Mean measured detection percentages for stroboscopic effects by light sources varying in flicker frequency and percent flicker (Bullough et al. in press). Also shown are the locations of several common light sources in terms of flicker frequency and percent flicker (HPS: 250 W high pressure sodium lamp; MH: 250 W metal halide lamp; WWF: 40 W warm-white halophosphor fluorescent lamp; INC: 100 W incandescent lamp).

Acceptability of Stroboscopic Effects

To assess acceptability of flicker producing noticeable stroboscopic effects, a five-point scale was used by Bullough et al. (in press):

+2 very acceptable
+1 somewhat acceptable
0 neither acceptable nor unacceptable
–1 somewhat unacceptable
–2 very unacceptable

The acceptability data from the study by Bullough et al. (in press) are shown in the contour plot in Figure 3, as a function of flicker frequency and percent flicker. Also shown in Figure 3 are the frequency and percent flicker values for several common light sources. None of the mean acceptability ratings were below –1.

The data in Figures 2 and 3 suggest that even when stroboscopic effects from flicker were readily detected, they were not always judged as unacceptable. For example, at 1000 Hz, detection of stroboscopic effects (Figure 2) was highly dependent upon the amount of modulation (percent flicker), but ratings of acceptability (Figure 3) were relatively high regardless of the percent flicker value.

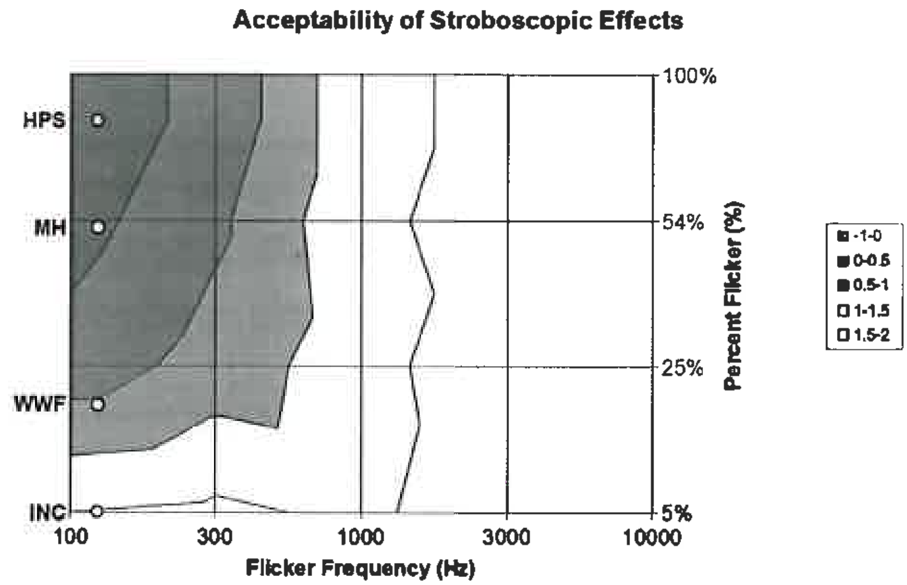


Figure 3. Mean measured acceptability ratings for stroboscopic effects by light sources varying in flicker frequency and percent flicker (Bullough et al. in press). Also shown are the locations of several common light sources in terms of flicker frequency and percent flicker (HPS: 250 W high pressure sodium lamp; MH: 250 W metal halide lamp; WWF: 40 W warm-white halophosphor fluorescent lamp; INC: 100 W incandescent lamp).

For rectangular waveforms operated so that the maximum and minimum light output are produced 50% of the time, the predicted acceptability (*a*, using the scale above) of noticeable stroboscopic effects can be quantified in terms of the frequency (*f*, in Hz) and percent flicker (*p*, in percent) as follows (Bullough et al. in press):

Step 1. Determine the frequency corresponding to the borderline between acceptability and unacceptability, f_b

For a given percent flicker value (*p*, in percent), the frequency at which a rating of zero, corresponding to the borderline between acceptability and unacceptability of stroboscopic effects (f_b, in Hz), is calculated as follows:

$$f_b = 130 \log p - 73$$

Step 2. Estimate the acceptability, a

For a given flicker frequency (*f*, in Hz), and using the borderline frequency (f_b, in Hz) calculated in Step 1, the resulting acceptability (*a*, based on the scale above) can be estimated as follows:

$$a = 2 - 4/(1 + f/f_b)$$

This equation is applicable to frequencies from 100 to 10,000 Hz and for percent flicker values from 5% to 100%. The visual task used to assess stroboscopic effects was waving a light-colored rod against a dark background (Bullough et al.

in press), and represents close to a worst-case scenario for perception of stroboscopic effects.

Example Calculations

Suppose a light source produces a rectangular waveform with the maximum and minimum light output each produced 50% of the time, with a frequency (f) of 350 Hz and percent flicker (p) value of 50%. To estimate the percent likelihood of detecting stroboscopic effects (d) under conditions similar to those used by Bullough et al. (in press), the following calculation is performed:

$$(25 \times 50 + 140)/(350 + 25 \times 50 + 140) \times 100\% = \mathbf{80\%}$$

Thus, under conditions similar to waving a light-colored rod against a dark background, the light source would be expected to produce noticeable stroboscopic effects 80% of the time.

For 50% flicker, the frequency at the borderline between acceptability and unacceptability (f_b) is calculated as follows:

$$130 \times \log 50 - 73 = 148 \text{ Hz}$$

Using a value for f_b of 148 Hz, the estimated acceptability rating for this condition is:

$$2 - 4/(1 + 350/148) = \mathbf{+0.81}$$

Thus, under conditions similar to waving a light-colored rod against a dark background, the light source would be expected to elicit an average acceptability rating of +0.81, corresponding approximately to somewhat acceptable.

Application of Calculation Methods

Because the study that assessed stroboscopic effects (Bullough et al. in press) used a light-colored, rapidly moving object viewed against a dark background, it comprises a near-worst-case condition for perception of stroboscopic effects. Slower movements, objects with lower contrast, and the presence of non-flickering light sources such as daylight would all be expected to reduce the likelihood of detecting, and to increase the acceptability of, stroboscopic effects from a flickering light source.

For this reason, a relative criterion for reducing the perception of stroboscopic effects is proposed. Further, a specification criterion based on the detection of stroboscopic effects rather than on acceptability is proposed, because this is likely to result in a more conservative specification. Reducing the detectability of stroboscopic effects is also likely to increase their acceptability, but not vice versa, based on the data in Figures 2 and 3.

Few people consider incandescent lamps to be problematic light sources in terms of flicker or stroboscopic effects, although these sources produce flicker that can result in noticeable stroboscopic effects. A 60 W incandescent lamp, when operated on a 60 Hz AC power supply, produces 8% flicker (Rea 2000). Using data from Rea (2000) and interpolating for a 50 Hz AC power supply, it is estimated that the same lamp would produce 10% flicker. If one desired to limit the detection of stroboscopic effects from an arbitrary light source to be no greater than under a 60 W incandescent lamp operated on 50 Hz AC power, the equation provided in the section above entitled "Detection of Stroboscopic Effects" could be rearranged to solve for the maximum percent flicker value (p_{max}) for a given frequency (f) that would result in stroboscopic effects no greater than those from a 60 W incandescent lamp, as follows:

$$p_{max} = 0.16f - 5.6$$

For example, if a particular driving circuit results in an LED source producing a flicker frequency of 120 Hz, the equation above would predict that the percent flicker value could be up to 14% and the source would not produce stroboscopic effects more perceptible than those from a 60 W incandescent lamp operated on 50 Hz AC power. If the flicker frequency were 250 Hz, the percent flicker value could be up to 34%.

For flicker frequencies higher than 660 Hz, the equation above will yield percent flicker values greater than 100%. This implies that for any frequency higher than this value, any amount of flicker will be less noticeable than that from the incandescent reference condition.

Caveats

As described above, the data underlying the equation in the previous section correspond to the perception of stroboscopic effects from a light source producing a rectangular waveform with the maximum and minimum light output each produced 50% of the time, and for a visual stimulus consisting of a light-colored rod being waved against a dark background, for frequencies between 100 and 10,000 Hz, and for percent flicker values between 5% and 100%. They are also only applicable when the flickering source is the only light source in a space. The presence of daylight from windows or other light sources with different flicker characteristics will reduce the perception of stroboscopic effects.

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About ASSIST

ASSIST was established in 2002 by the Lighting Research Center at Rensselaer Polytechnic Institute as a collaboration among researchers, manufacturers, and government organizations. ASSIST's mission is to enable the broad adoption of solid-state lighting by providing factual information based on applied research and by visualizing future applications.

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Effects of flicker characteristics from solid-state lighting on detection, acceptability and comfort

JD Bullough PhD, **K Sweater Hickcox** BFA, **TR Klein** MS and **N Narendran** PhD
Lighting Research Center, Rensselaer Polytechnic Institute, Troy, New York, USA

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A study to assess the detection and acceptability of flicker and stroboscopic effects under different lighting conditions was conducted. Frequencies from 50 Hz to 300 Hz were assessed, as well as different modulation amounts, duty cycles, waveform shapes and correlated colour temperatures. For the range of conditions evaluated, direct perception of flicker was negligible at 100 Hz or higher, but stroboscopic effects could be perceived at 300 Hz. Reducing flicker modulation from 100% to 33% decreased perception of stroboscopic effects. A higher duty cycle was associated with slightly lower discomfort. The implications for solid-state lighting systems producing high-modulation flicker are discussed.

1. Introduction

Flicker is the rapid modulation of light in a cyclical manner. Human visual sensitivity to flicker depends upon a number of factors, including the flicker frequency, the amount of modulation (the difference between maximum and minimum light output divided by the sum of the maximum and minimum light output) or flicker index[1] (the area under a light-output/time curve above the average light output divided by the entire area under the light-output time curve, for a single flicker cycle), the absolute light level and the location in the visual field.[2] The factors that seem to have been studied most are frequency and the amount of modulation. Classic data from Kelly[3] for modulation of large (30° radius) visual fields at different light levels from 0.03 to 5000 cd/m^2 showed that beyond 100 Hz, even flicker with 100% modulation was hardly ever *directly* visible, either centrally or peripherally.

Flicker can also be perceived *indirectly* through stroboscopic effects. One example is the wagon-wheel effect, whereby a spoked wheel rotating at a particular speed can appear to be rotating at a different speed, or even to be stationary, under flickering light. Another stroboscopic phenomenon, known as a phantom array, can be perceived when a rapidly flickering light source is in view during a rapid eye movement (saccade); an individual will report seeing an array of sources between the pre- and post-saccade fixation points. Of interest, these stroboscopic visual effects are robust even at frequencies where flicker cannot be perceived directly (i.e. when data from Kelly[3] indicate that flicker is not visible). Rea and Ouellette[4] reported that spectators viewing a table-tennis match under illumination from high-intensity discharge (HID) sources exhibiting 120 Hz flicker with high modulation (84% flicker, 0.25 flicker index) could detect stroboscopic motion of the ping-pong ball, but when the modulation was lower (51% flicker, 0.15 flicker index), stroboscopic motion was barely noticeable. Hershberger and Jordan[5] operated a single light-emitting diode (LED) at 200 Hz (100% flicker, 0.8 flicker index) and 97% of the subjects in their study detected a stroboscopic phantom array when they shifted their visual

Address for correspondence: Dr John Bullough, Lighting Research Center, 21 Union Street, Troy, NY 12180, USA. E-mail: bulloj@rpi.edu

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fixation from one point to another. Hershberger et al.[6] reported that a phantom array was visible by most of their subjects even at 500 Hz. Veitch and McColl[7] compared visual performance and visual comfort under fluorescent lighting systems operated on magnetic (120 Hz, 43–98% flicker, 0.14–0.33 flicker index) and electronic (20 000 + Hz, percent flicker and flicker index not reported) ballasts and found small differences in performance, but not comfort, between them. Noritake et al.[8] found that the localisation of objects when making saccades was less accurate for a flickering stimulus (200 Hz, 100% flicker, 0.8 flicker index); it is possible that these misjudgements could contribute to discomfort over time, although this is speculation. In addition to the factors listed above, other factors can also impact the direct or indirect perception of flicker:[9]

- Duty cycle (defined as the percentage of time within a waveform that the light output exceeds 10% of the maximum output)
- Waveform shape
- Colour

This paper contains a description of a laboratory experiment designed to assess the relative impact of flicker frequency, amount of modulation, duty cycle, waveform shape and correlated colour temperature (CCT) on visual perception and acceptability. The study's context is the use of alternating current (AC) LEDs in lighting applications. This means that the selection of specific characteristics used in the experiment correspond to conditions that might occur in the development of lighting systems using AC LEDs.

The present study is not an assessment of health effects of flicker from lighting systems. There is evidence[10] that flicker, especially between 15 and 20 Hz (which is directly visible), can induce seizures in persons with photosensitive epilepsy and that flicker that cannot be perceived directly (at 100–120 Hz) can lead to headaches and eye strain in a portion of the general population.[11] The Institute of Electrical and Electronics Engineers (IEEE) is presently working on a standard (P1789) for the luminous flicker from solid-state lighting technologies to minimise negative visual and non-visual impacts of flicker from these systems.

2. Method

In a dark-painted windowless room at the Lighting Research Center at Rensselaer Polytechnic Institute, a workstation containing a laptop computer, a clipboard taking letter size paper and a task luminaire was set up (Figure 1). The head of the luminaire was at the end of a flexible conduit and contained three LED sources: two high-power (20 W) LEDs (with CCTs of 2700 K and 4000 K) that operate on direct current (DC) and one high-power (3 W) AC LED (with a CCT of 6000 K). All of the LEDs were mounted near the centre of a circular metal plate that was recessed into the head of the luminaire. The interior of the luminaire head was painted matte white; no other optics were used.

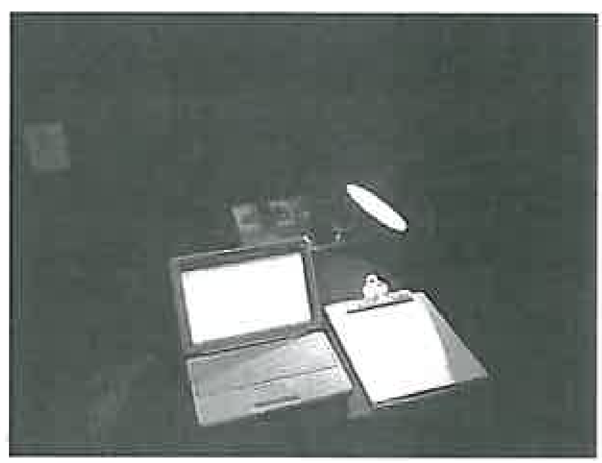

Figure 1 View of the test laboratory from the subject's seating position

The AC LED produced 120 Hz luminous flicker with a chopped sinewave waveform and was operated using power from a nearby 120 V wall plug. When energised, the task luminaire produced a horizontal illuminance of 400 lux on the centre of the desktop adjacent to the laptop computer. A custom current source was designed for powering the LEDs. The current source generated user-determined, variable-modulation-depth rectangular light waveforms at selected frequencies. It consisted of a microprocessor controller with pulse-width modulation (PWM) generators, constant-current sources, field-effect transistors (FETs) and a power supply. The current feeding into the LED for a given condition was determined by steering the current either to the LED or shunting it around the LED with a FET, which eliminated turn-on and thermal transients. Six individual current sources, in a binary sequence, enabled the current to be modulated within one part in 64 (i.e. with a resolution of about 1.6%). The waveform was generated by setting the high and low current values in the PWM generators to obtain the desired light output levels and by setting the reload rate to determine the frequency. The microprocessor was fast enough to generate correct waveforms with frequencies up to 10 kHz.

Because the DC LEDs were higher-power devices than the AC LEDs, the overall currents used to operate them under each condition were adjusted to provide the same illuminance that was produced by the AC LED (400 lux). All three LEDs had similar angular distributions (125°–130° viewing angles) and the pattern of light produced by the luminaire was very similar for all three LEDs. The luminaire was always angled slightly during each experimental session so that the bare LEDs were not visible (their bare luminances would have been very glaring) but a portion of the white interior of the luminaire head was visible, as illustrated in Figure 1, to provide a condition whereby direct, on-axis perception of flicker could be assessed. A total of nine different conditions were used in the experiment, as listed in Table 1. Figure 2 shows the relative light waveforms for each condition, normalised to the same time-averaged value (denoted by the dashed line). Conditions 6 and 9 had the same flicker characteristics, with differences in CCT only, so only eight waveforms are shown in Figure 2.

Posted on the wall facing the subjects in the laboratory were two small placards labelled A and B (placard A is barely visible in the left-side portion of Figure 1). The approximate angular positions from the subjects' point of

Table 1 Summary of experimental conditions used in the experiment

Condition	Flicker frequency (Hz)	Percent modulation (%)	Flicker index	Duty cycle (%)*	Waveform	Correlated colour temperature (K)
1	50	100	0.50	50	Rectangular	4000
2	60	100	0.50	50	Rectangular	4000
3	100	100	0.50	50	Rectangular	4000
4	120	100	0.50	50	Rectangular	4000
5	300	100	0.50	50	Rectangular	4000
6	120	100	0.90	10	Rectangular	4000
7	120	33	0.17	100**	Rectangular	4000
8	120	100	0.41	60	Chopped sinewave	6000
9	120	100	0.90	10	Rectangular	2700

*Percentage of time light output > 10% of maximum.
**Duty cycle is 50% for the modulating portion of the waveform only.

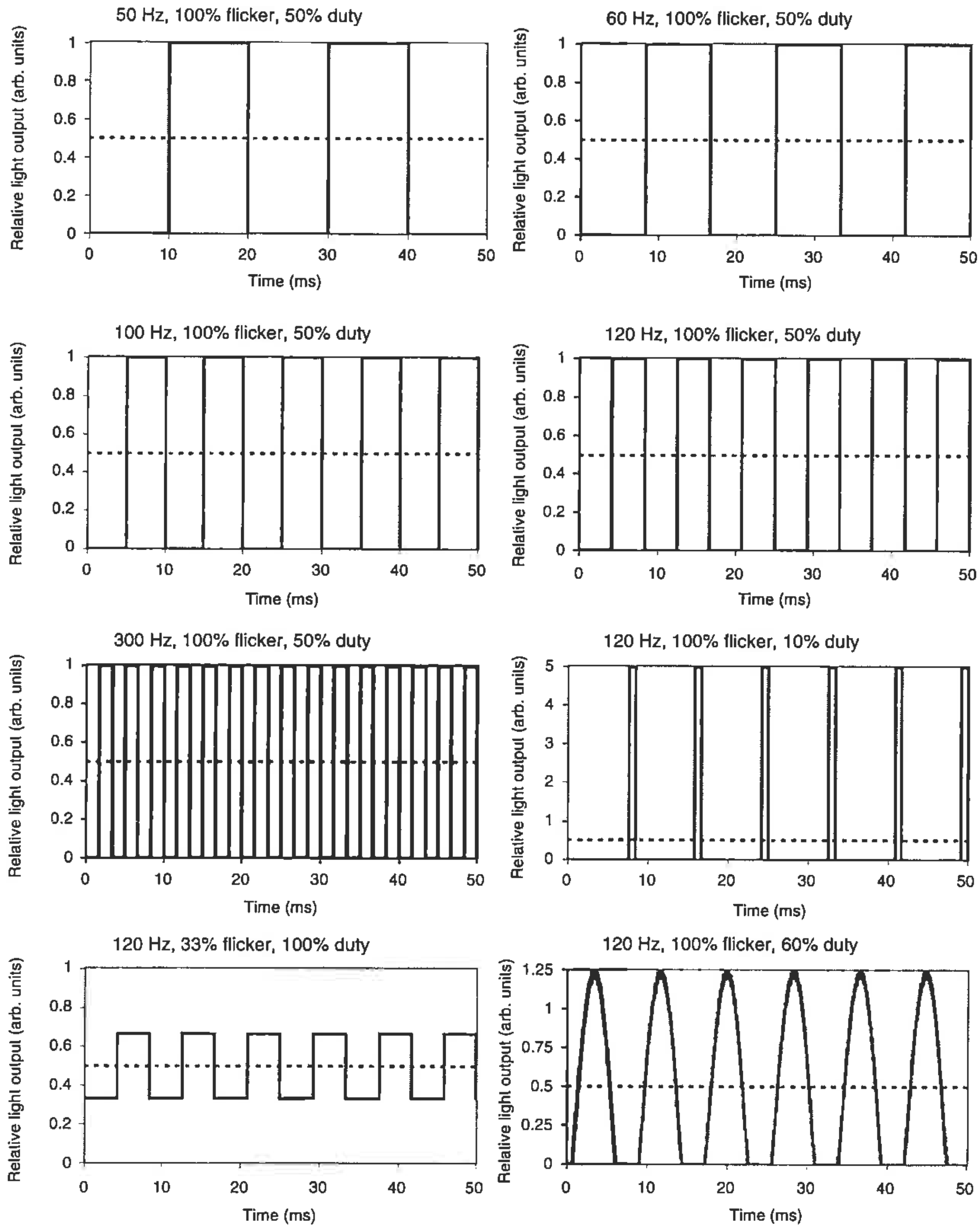

Figure 2 The normalised waveforms used

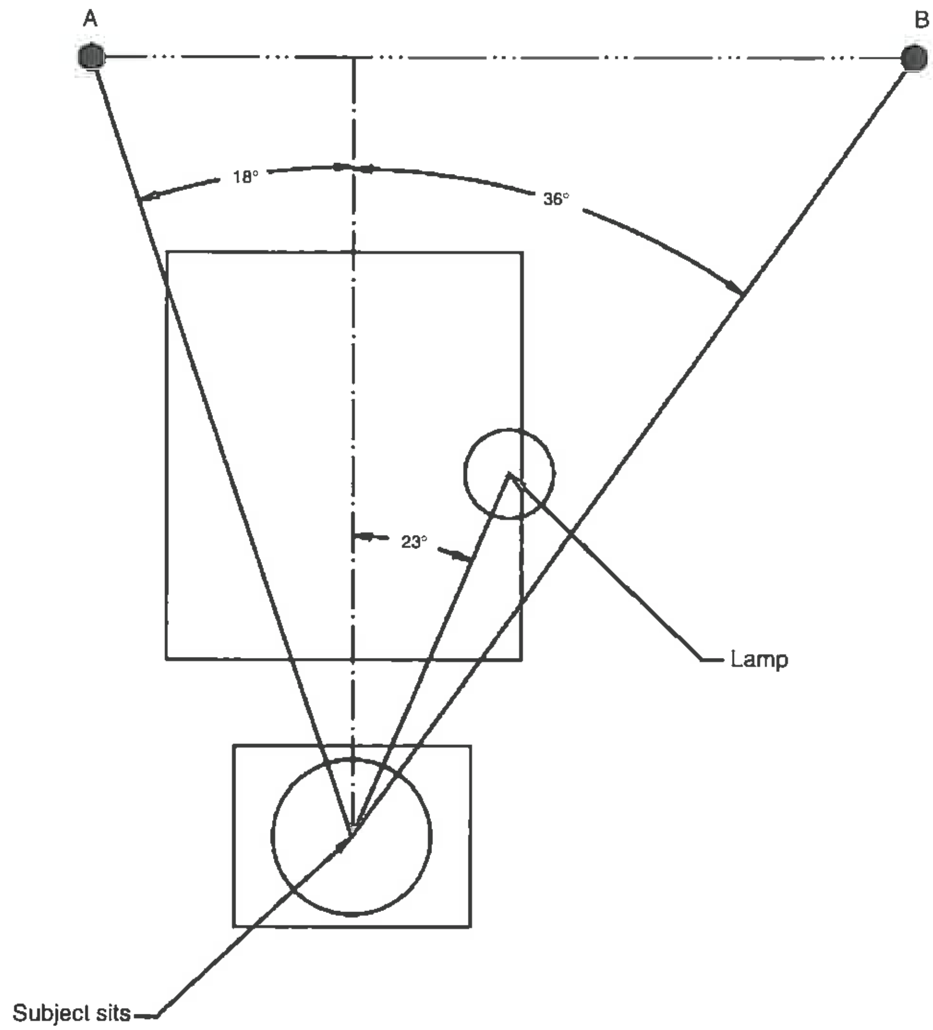

Figure 3 Approximate angular positions of objects in the subject's field of view

view of each placard and of the luminaire are illustrated in Figure 3.

Upon entering the laboratory and signing an informed consent form approved by Rensselaer's Institutional Review Board, ten volunteer subjects (three female/seven male, aged 23–55 years, mean 34 years, s.d. 10 years) participated in the study. Subjects wore corrective lenses if necessary. No subjects who reported a history of migraines or epileptic seizures participated in the study.

For each experimental session, all of the conditions in Table 1 were presented in a randomised order. After each condition was switched on, subjects were asked to perform six simple arithmetic problems (a different set for each lighting condition) displayed on the screen of the laptop computer (a liquid crystal display with a screen refresh rate of 60 Hz) and then to complete a one-page, written-question survey questionnaire on the clipboard next to the computer. The first question pertained to their perception of flicker (if any) while they were working on the computer. After completing that question, subjects were asked to fold the laptop screen down and answer additional questions. Each of the six questions can be summarised as follows:

- Q1: Was flicker noticed while using the computer?
- Q2: Was flicker noticed while looking directly at the luminaire?
- Q3: Was flicker noticed while looking at point A (a visual angle of approximately 40° from the luminaire)?
- Q4: Were flicker or stroboscopic effects noticed after subjects were asked to shift their gaze between points A and B in the room (separated by a visual angle of approximately 54°)?
- Q5: Were flicker or stroboscopic effects noticed after subjects were asked to wave their hand underneath the luminaire?
- Q6: How comfortable was the lighting?

Questions Q1 through Q3 pertained mainly to direct perception of flicker, Q4 and Q5 pertained to indirect perception of flicker through stroboscopic effects and Q6 pertained to the overall level of comfort. Q1 through Q5 were two-part questions consisting of a yes/no response (e.g. was flicker detected) that all subjects answered and a five point rating scale of acceptability (−2: very unacceptable, −1: somewhat unacceptable, 0: neither acceptable nor unacceptable, +1: somewhat acceptable, +2: very acceptable) that was answered only if the first part was answered in the affirmative. Q6 used a five-point rating scale of comfort (−2: very uncomfortable, −1: somewhat uncomfortable, 0: neither comfortable nor uncomfortable, +1: somewhat comfortable, +2: very comfortable). After completing the last question, the lighting condition was changed to another randomly ordered one from Table 1, and the procedure was repeated until all nine conditions had been tested. The entire experiment took approximately 20 minutes for each subject to complete. Because there were ten subjects, the resolution of the mean detection percentages is 10% and the resolution of the mean subjective ratings is 0.1.

3. Results

To assess the impacts of each factor in the experimental design, different subsets of conditions from Table 1 were compared, in which the other factors were held fixed, as follows:

- To assess the effect of flicker frequency, conditions 1–5 were compared.
- To assess the effect of different amounts of modulation, conditions 4 and 7 were compared.
- To assess the effect of duty cycle, conditions 4 and 6 were compared.
- To assess the effect of waveform shape, conditions 4 and 8 were compared.
- To assess the effect of CCT, conditions 6 and 9 were compared.

Using this experimental design, each of the five main effects could be studied efficiently with nine experimental conditions. A factorial design experiment with five values of flicker frequency and two values each of modulation amount, duty cycle, waveform shape and CCT would have required 80 ($5 \times 2 \times 2 \times 2 \times 2$) trials for each subject, drastically increasing the time required to complete the experiment and potentially confounding the results with fatigue and boredom. A disadvantage of this experimental design is that interactions among the factors can not be assessed.

3.1. Flicker frequency

The percentages of time each flicker frequency value was detected, after working on the laptop computer, are shown in Figure 4(a). To assess detection, the number of yes responses to Q1a were compared among the frequencies using a Cochran Q test, with a statistically significant ($p < 0.05$) effect of frequency identified. Detection of flicker at

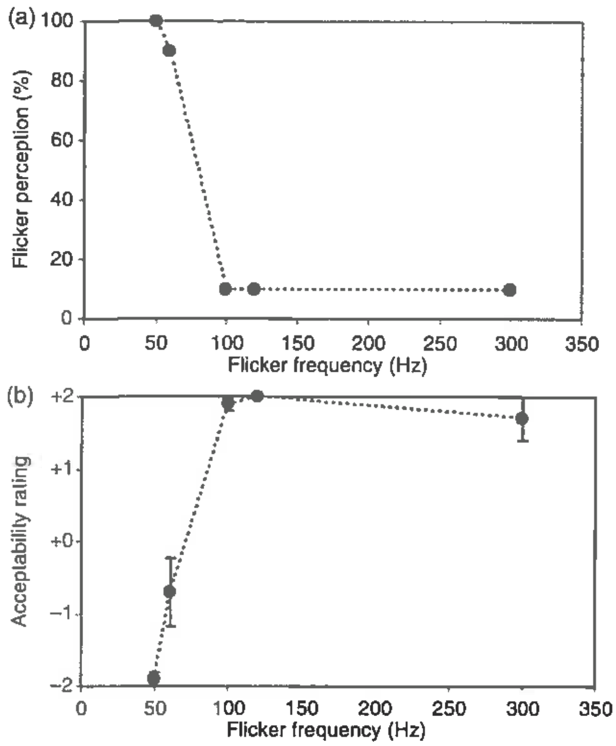

Figure 4 Percentage detection of flicker for different frequencies (a), and mean (±s.e.m.) acceptability ratings (b), after working on the laptop computer

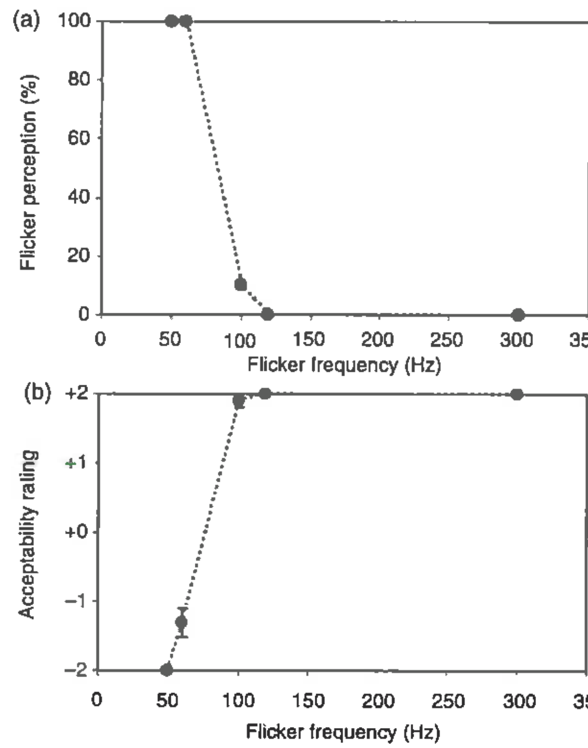

Figure 5 Percentage detection of flicker for different frequencies (a), and mean (±s.e.m.) acceptability ratings (b), when viewing the luminaire directly

50 and 60 Hz was very high (≥90%) and detection at frequencies of 100 Hz and higher was very low (≤10%). This suggests that the critical frequency for flicker detection is between 60 and 100 Hz, consistent with data from Kelly.[3]

Assuming the acceptability responses for Q1 would have been +2 (very acceptable) for subjects who did not perceive flicker (responses to all of the acceptability portions of Q1 through Q5 were treated similarly), Figure 4(b) shows the mean acceptability ratings for each frequency, together with the associated standard error of the mean (s.e.m). The data in Figure 4(b) mirror those in Figure 4(a) and a one-way within-subjects analysis of variance (ANOVA) revealed a statistically significant ($p<0.05$) effect of frequency. Mean acceptability ratings for Q1 at frequencies of 100 Hz and higher were very close to +2, and were negative (implying unacceptability) for the lower frequencies.

For direct perception of flicker when looking at the white reflector of the luminaire (Q2), a Cochran Q test on the number of affirmative responses among each frequency (Figure 5(a)) revealed a statistically significant ($p<0.05$) effect of frequency. Flicker was unanimously detected at 50 and 60 Hz and rarely (≤10%) at 100 Hz and greater frequencies. A one-way within-subjects ANOVA on the acceptability ratings for Q2 also revealed a statistically significant ($p<0.05$) effect of frequency, with very acceptable mean ratings at frequencies of 100 Hz and higher, and negative ratings at 50 and 60 Hz (Figure 5(b)).

When subjects viewed point A on the wall ahead, located at a visual angle of about 40° from the luminaire, a Cochran Q test on the number of affirmative responses to the first part of Q3 (Figure 6(a)) revealed a statistically significant ($p<0.05$) effect of frequency. The proportions of yes responses at 50 and 60 Hz were equal to or greater than 70%; at the higher frequencies ($\geq$100 Hz) no flicker was detected. A one-way within-subjects ANOVA on the acceptability ratings for Q3 also revealed a statistically significant ($p<0.05$) effect of frequency. Mean ratings were very acceptable at 100 Hz and higher frequencies, but only slightly unacceptable at lower frequencies (Figure 6(b)).

When asked to shift their gaze between points A and B on the wall ahead (Q4), there was a decreasing number of yes responses as the frequency increased (Figure 7(a)) and a statistically significant ($p<0.05$) effect of frequency was found with a Cochran Q test on the number of affirmative responses among the frequencies. Detection of flicker or stroboscopic effects averaged 80% at 50 and 60 Hz and 50% at 100 Hz, and at the highest frequency (300 Hz) the average detection percentage was 30%. A one-way within-subjects ANOVA on the acceptability ratings for Q4 (Figure 7(b)) revealed a statistically significant ($p<0.05$) effect of frequency. Even though about one-third to one-half of the subjects could detect flicker or stroboscopic effects at 100 Hz and higher frequencies, the subjective ratings indicated high levels of acceptability (mean rating values from +1.8 to +2).

For Q5, where subjects waved their hand underneath the luminaire to determine if they could detect stroboscopic effects such as the appearance of multiple images of their fingers, a Cochran Q test on the number of yes responses to the first part of the question

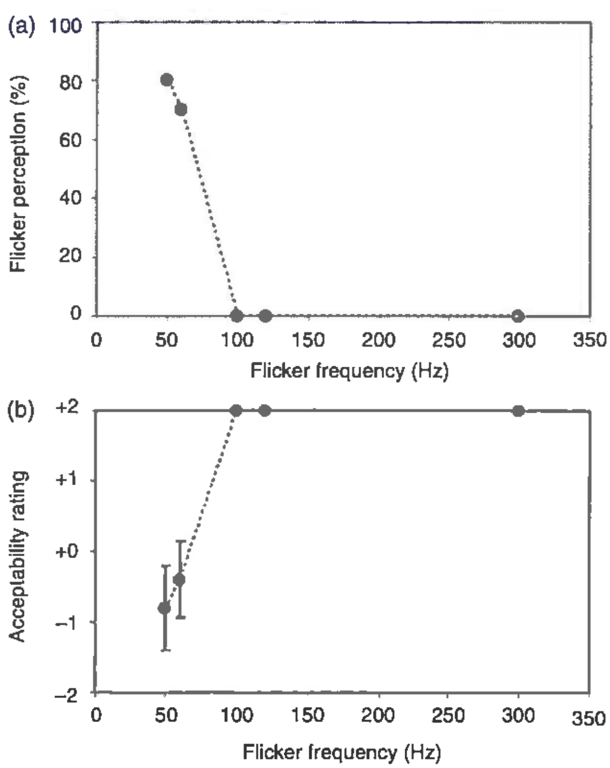

Figure 6 Percentage detection of flicker for different frequencies (a), and mean (±s.e.m.) acceptability ratings (b), when viewing away from the luminaire

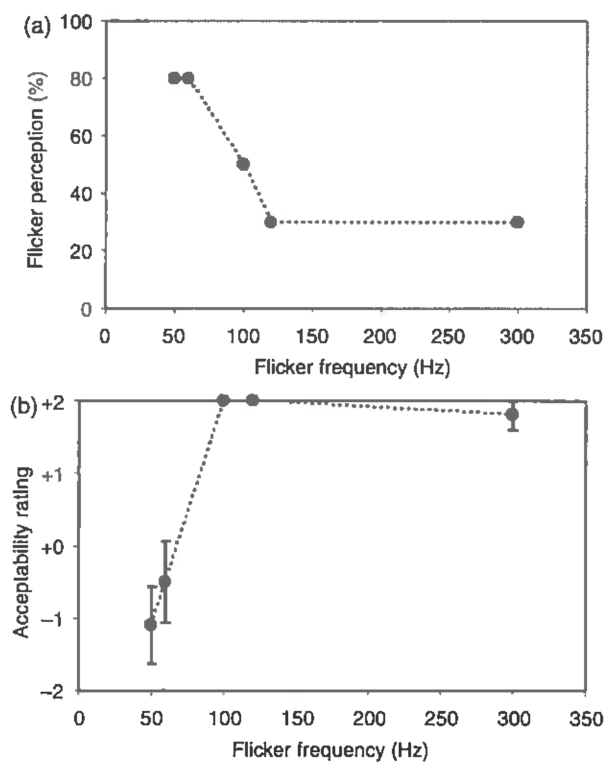

Figure 7 Percentage detection of flicker/stroboscopic effects for different frequencies (a), and mean (±s.e.m.) acceptability ratings (b), when looking back and forth between points A and B

revealed a statistically significant ($p<0.05$) effect of frequency. The majority of subjects could detect the stroboscopic effect for all frequencies at or below 120 Hz and at 300 Hz, 40% could see the effect (Figure 8(a)). There was also a statistically significant ($p<0.05$) effect of frequency on the acceptability ratings, according to a one-way, within-subjects (ANOVA). The mean ratings increased from 50 to 100 Hz and were moderately acceptable from 100 to 300 Hz (Figure 8(b)).

Finally, when subjects were asked to rate the overall level of comfort from each lighting condition (Q6), a one-way, within-subjects ANOVA on these ratings indicated that there was a statistically significant ($p<0.05$) effect of frequency, with negative ratings for 50 and 60 Hz and positive ratings at 100 Hz and higher (Figure 9).

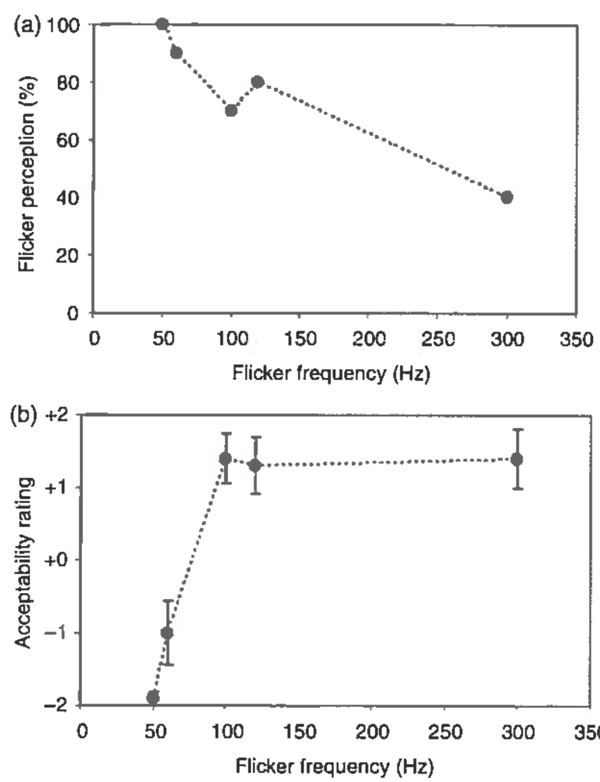

Figure 8 Percentage detection of flicker/stroboscopic effects for different frequencies (a), and mean (±s.e.m.) acceptability ratings (b), when moving a hand directly below the luminaire

3.2. Amount of modulation

To evaluate the impact of the amount of modulation on flicker perception (at 120 Hz), binomial proportion tests were performed on the number of yes responses to each of the questions Q1a–Q5a; two-tailed paired *t*-tests were performed on the acceptability ratings for questions Q1b–Q5b and on the comfort ratings for Q6. The only statistically significant ($p<0.05$) effects identified were for questions Q4a (when looking back and forth between two locations) and Q5a (when waving a hand under the luminaire). For question Q4a, when modulation was higher (100% flicker, 0.5 flicker index), flicker or stroboscopic effects were detected about one-third of the time. When modulation was lower (33% flicker, 0.17 flicker index), these effects were never detected. For question Q5a, when modulation was higher, subjects saw the stroboscopic effects most of the time (80%) and when the modulation was lower, stroboscopic effects were only detected some of the time (30%).

3.3. Duty cycle

Binomial proportion tests were conducted on the detection percentages for Q1a through Q5a, and two-tailed paired *t*-tests were conducted on the acceptability ratings for Q1b through Q5b and on the comfort ratings for Q6, between the 50% and 10% duty cycles

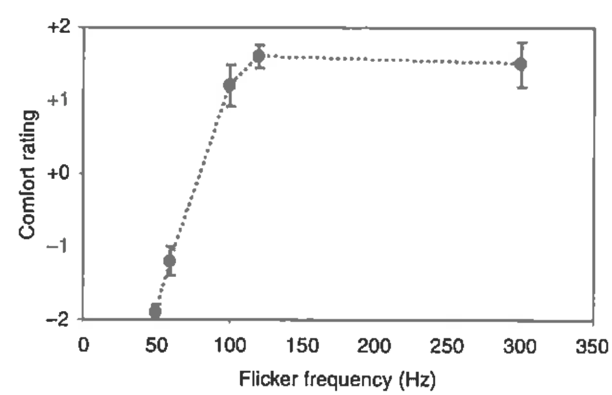

Figure 9 Mean (±s.e.m.) overall comfort rating for each flicker frequency

(at 120 Hz; for the 10% duty cycle, the LED was off 90% of the time). The only statistically significant ($p < 0.05$) effect was for the overall comfort level, although the magnitude of the effect was quite small. The mean rating was between +1 and +2 for the 50% duty cycle and slightly lower than +1, for the 10% duty cycle (Figure 10).

3.4. Waveform shape and CCT

Binomial proportion tests on the detection responses for questions Q1a through Q5a and two-tailed paired *t*-tests on the acceptability ratings for Q1b through Q5b and on the comfort ratings for Q6, revealed no statistically significant ($p > 0.05$) effects of either the waveform shape (rectangular or chopped sinewave) or of the change in CCT from 2700 to 4000 K. Indeed, since the AC LED used in the luminaire had a higher CCT than the DC LED with which it was compared, the comparison between conditions 4 and 8 in Table 1 also indirectly assessed a CCT difference (4000–6000 K), but none of the responses to any of the questions were significantly different between the two LED conditions.

4. Discussion

For the range of conditions used, the variables that exerted the most influence on direct and indirect perception of flicker were the frequency, the amount of modulation and the duty cycle. For practical purposes, the waveform shape and the CCT of the LED illumination had no effect on flicker perception or on comfort under these conditions.

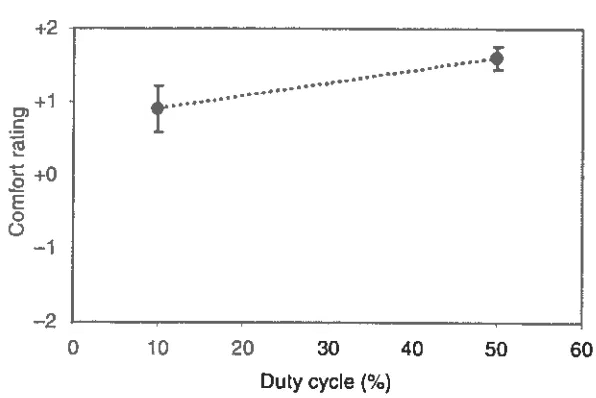

Figure 10 Mean (±s.e.m.) overall comfort rating for each duty cycle

The results regarding the influence of flicker frequency on direct perception of flicker are entirely consistent with those of Kelly.[3] At frequencies of 100 Hz and higher, perception of flicker while working on the laptop computer, while looking directly at the luminaire or while looking at an angular location remote from the luminaire, was negligible. Direct perception of flicker at frequencies of 60 Hz and lower was possible and was rated as unacceptable. In contrast, indirect perception of flicker through stroboscopic effects was lower for the higher frequencies but was not obliterated completely, even at 300 Hz. Nonetheless, subjects rated their perception of these effects as quite acceptable as long as the frequency was at least 100 Hz.

Regarding modulation, the present results suggest that, at least for the conditions used in the experiment, reducing the modulation from 100% flicker to 33% flicker was successful at reducing perception of stroboscopic effects. In fact, when subjects switched their direction of gaze back and forth between two points in the field of view, a binomial proportion test revealed that they were statistically significantly ($p < 0.05$) more likely to detect a stroboscopic effect under 100% flicker with a frequency of 300 Hz, than under 33% flicker at 120 Hz. These results are consistent with those of Rea and Ouellette[4] who found that reduced modulation (51% flicker, compared to 84% flicker) substantially reduced the perception of stroboscopic effects.

For the effect of duty cycle on comfort (Q6), there was somewhat lower comfort under the lower duty cycle. Experimenters observed that stroboscopic effects under the 10% duty cycle appeared to be more prominent than under any of the conditions with higher duty cycles. Interestingly, the responses to Q1 through Q3 involving direct perception of flicker with a 10% duty cycle all revealed very similar responses and acceptability ratings as with the same frequency but a 50% duty cycle, suggesting that this factor has a small role in direct perception of flicker at this frequency. Only for the latter questions (Q4 and Q5) were indirect perceptions of flicker through stroboscopic effects somewhat differentiated between the 10% and 50% duty cycles, although these were not statistically significant differences.

There are several limitations to the present study. A single light level was employed. The study was conducted in a dark, windowless room, with all illumination provided by a single task luminaire near the work surface, conditions that are not particularly representative of those in many lighting applications, except perhaps for some computer drafting rooms. In addition, when windows are present, the resulting modulation of any electric lighting will be reduced, probably reducing indirect perception of flicker through stroboscopic effects. The participants in this study were healthy adults with nominally normal or corrected vision. Individuals who might experience headaches under low-frequency fluorescent lighting,[11] or who have a history of epileptic seizures,[10] did not participate in the study and so the results do not apply to these sub-populations. The study did not assess interactions between any of the independent variables.

In general, the results of the study suggest that AC LEDs with light waveforms like the one used in the present study, operating on line frequencies and producing flicker frequencies of 120 Hz (most of North and South America) or 100 Hz (in most of Europe, Asia, Africa and Australia), will not generate directly perceptible flicker either when looking at or looking away from the source of illumination. Even when indirect perception of flicker through stroboscopic effects was visible, it was generally rated positively (somewhat or very acceptable). The results also suggest that if there is any room for improvement in the operation of some AC LEDs such as those with waveforms like the one used in this study, it might in certain situations be better served by adding a steady component to the modulation (thereby reducing percent flicker and flicker index) than by increasing the flicker frequency.

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EUROPEAN COMMISSION
DIRECTORATE-GENERAL JRC
JOINT RESEARCH CENTRE
Institute for the Energy
Renewable Energy Unit

10 February 2011

EUROPEAN
LED QUALITY CHARTER

An initiative promoted by

the European Commission Joint Research Centre

1. INTRODUCTION

The European Commission together with several national governments, energy agencies, public and private organisations/industries is promoting the end-use energy efficiency in lighting through several instruments as a key component of the EU energy policy and the common goal of reducing climate change.

In EU, the total domestic lighting consumption is around 86 TWh and it is predicted to raise to 102 TWh by 2020 due to growing welfare especially in some countries and rapidly increasing number of lamps per home. LED lamps efficacy and luminous characteristics are improving very rapidly. In the future, LED lamps are expected to deliver substantial energy savings. LED lamps last 5-25 times as long as the traditional lamps.

GLS and some halogen lamps are about to be phased out due to EU regulation (Eco-design). In many cases, LED lamps are a valid retrofit solution. During this decade it is expected that LED lamps will cover nearly all types of lamps. At present, LED lamps are nearly not used for indoor lighting in the residential sector but the market penetration is starting.

The challenge is to retrofit incandescent lamps with LED lamps of good quality – alternatively users will install mainly new halogen lamps with only slightly lower energy consumption. The barriers for this development are actual high prices for LED lamps of good quality and the variation in performance of LED sources in the market is far too large. Many customers may have bad experience with use of LED lamps and that will threat consumer confidence in LED lighting performance and savings. This might give a delay in market acceptance and a slowing down of the LED penetration rate.

The availability of good quality products is thus most essential along with information about the high energy efficiency and the savings for the consumer. Since the actual price of LED lamps of good quality is high, governments, municipalities and/or utilities may subsidise the LED lamps. A LED quality charter is needed in these activities, to assure public money is spent on lamps delivering real savings.

More than 20 years ago when the CFL product was introduced at the market the situation was quiet similar. After buying the first CFLs many consumer were very dissatisfied and rejected the technology. It took many years and a lot of work to overcome the barriers created during the first years at the market. It is very important not to repeat these failures when the LED is introduced at the market.

Development of the market for LED lamps is thus very important to increase energy efficiency and reduce CO_2 emissions in the European Union. Standards and Eco-design regulation are coming within the next year. The role of the European LED Quality Charter is to set a important voluntary requirements for white LED lamps (not covering LED chips, modules or luminaires) that can be used now by governments, municipality, energy savings, utilities and other active parties to ensure the quality of LEDs on the market.

2. GOALS AND SCOPE

The European Quality Charter for LED is developed in 2010 on the initiative of the European Commission Joint Research Centre (JRC) to support the European initiatives for the Promotion of Efficient Lighting in the Residential Sector. It is a voluntary initiative.[1]

The scope of the present version LED Quality Charter is limited to **LED lamps intended primarily for use in the residential sector**. At this stage the European Quality Charter for LED does not include LED modules, luminaires and lamps specific for use in the commercial sectors. This limitation is due to the urgent need to publish a quality charter as soon as possible for support of customers replacing banned incandescent lamps (GLS and some halogen lamps), and other promotion programme at national or local level (e.g. white certificates).

The aim of the European LED Quality Charter is to offer a high quality voluntary standard to be used by European utilities, industries and other bodies for:

1. Manufacturing, marketing and/or sales of high quality LED lamps in the European Union
2. Raising consumer awareness and confidence in the LED, by assuring an acceptable quality and performance level are reached.
3. Supporting promotion and procurement campaigns providing quality, comfort, energy and money saving and decreasing the CO_2 emission.

The final goal of the European LED Quality Charter is thus to further increase the sales and penetration of high quality and efficient LEDs in the EU and thus contribute to the goals of the EU energy and environmental policies.

The European LED Quality Charter is a voluntary set of criteria established by the European Commission JRC in collaboration with a number of private and public organisations, including:

- Danish Energy Agency
- The Danish Energy Saving Trust
- NL Agency
- STEM

The European LED Quality Charter is open to all organisations who are willing to support and promote the present European LED Quality Charter in their recommendations to public and private organisations and when running promotion of LED lamps meeting the requirements of the European LED Quality Charter.

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[1] The background for the quality charter requirements is described in a EuropeanLED Quality Charter Background report.

3. PARTICIPATION

The present European LED Quality Charter is a voluntary scheme open to:

- LED manufacturers, importers and retailers marketing in Europe LED lamps that meet the requirements of the European LED Quality Charter;

- Private and public organisations (electricity distribution companies, public authorities, housing associations, hotels etc,), that will use the requirements of the European LED Quality Charter for their LEDs promotion, procurement, and DSM campaigns.

Participating lamp manufacturers, LEDs importers and retailers agree to promote in the market LEDs, which meet all the requirements of the European LED Quality Charter. They may use the European LED Quality Charter logo[2] only to indicate that the company is participating in this scheme and in advertisement, information material only in connection with products that meet the criteria. The logo shall not be used on individual products or their packaging.

The Commission reserve the right to test, review or ask for additional information for any product that a participating manufacturer claims is meeting the European LED Quality Charter criteria.

For private and public organisations using the European LED Quality Charter for their promotion/procurement/DSM campaigns, it is recommended:

- to use the Quality Charter in promotion, procurement and DSM campaigns;
- to communicate to the end-users (where applicable) that this is a joint European initiative on quality end-use efficiency initiated by the European Commission Joint Research Centre and the other organisations;

Each organisation willing to participate is requested to send the attached registration form along with a list of LEDs fulfilling the Charter Requirements to:

Paolo Bertoldi
European Commission, Joint Research Centre,
I-21020 Ispra (Va)
Tel +39 0332 78 9299, Fax. +39 0332 78 9992
e-mail: paolo.bertoldi@ec.europa.eu

With the permission of the participating company the Commission Joint Research Centre will disseminate the results of specific promotion/DSM campaign as "best practices" examples, acknowledging the contribution of the specific company.

4. ADDITIONAL INFORMATION

2 As of 21 February the logo is not yet finalised. A new Annex with the logo will be distributed and posted on the web in March 2011

Additional information on the European LED Quality Charter including a list of participating manufacturers is available on the Internet at:

http://energyefficiency.jrc.cec.eu.int/

EUROPEAN LED QUALITY CHARTER

PARTNERSHIP COMMITMENT SUBMISSION FORM

The company

………………………………………………………………………………

declares its willingness to:

- use the requirements of the European LED Quality Charter for their promotion, procurement, and DSM campaigns
- manufacturers, importers and retailers marketing in Europe LED lamps that meet the requirements of the European LED Quality Charter

Person responsible appointed by the company:

Name person: ______________________

Managerial Function: ______________________

Address: ______________________

Tel. / Fax: ___________ / ___________

e-mail/ internet: ______________________

Director or person authorised to sign for the organisation:

Name: ______________________

Managerial Function: ______________________

Address: ______________________

Tel. / Fax: ___________ / ___________

e-mail/ internet: ______________________

Signature ______________________

Date ______________________

Please send the signed submission form by email, fax or post to :

Paolo Bertoldi

European Commission, Joint Research Centre

TP 450

I-21027 Ispra (VA)
Tel. +39 0332 789299 Fax. +39 0332 789992
E-mail: paolo.bertoldo@ec.europa.eu

5. WHAT ARE the MAIN PROBLEMS WITH LED QUALITY?

The technology and performance of white LEDs are developing very fast. Actually, the availability of specific LED products at the market is very short as new and more efficient LEDs come on the market every six months. For customers buying LEDs one or two times a year, it is difficult if the products are different every time they visit the shop.

Some testing programs[3] have also found that the performance within individual batches of identical sources varied as much as 40%. That indicates that the actual manufacturer has not performed a proper binning maybe caused by downward pressure on pricing increase the temptation for manufacturers to "cut corners".

Some manufacturers overstate their LED performance and consumers unlucky enough to purchase low performing LEDs (not performing as claimed by the manufacturer) may be very dissatisfied and reject the technology, and the overall reputation of LED will suffer.

LED luminaires and replacement lamps available today often claim a long lifetime, e.g. 50,000 hours. These claims are based on the estimated lumen depreciation of the LED used in the product and often do not account for other components or failure modes. Lifetimes claimed by LED luminaire manufacturers should take into account the whole lighting system. Anyway in order to set requirements quickly in the actual emerging market, the present version of the European LED Quality Charter only sets requirements to the lifetime of the lamp.

LED's are often integrated permanently into the fixture/luminaire, making their replacement difficult or impossible – this may be could be all right if the lamp lifetime is 50,000 hours but it could be a problem if the lifetime is short. One of the key lessons learned from early market introduction of CFLi[4] is that long life claims need to be credible with appropriate manufacturer warranties.

A very long lifetime of 30-50,000 hours is somehow abstract as the lamps might rest at least 40-60 years pending on the yearly operation time. This means that the lamp might burn longer time than the luminaire is in use, the owner live in the home or live. A much shorter lifetime might be all right if the price of the LED is acceptable (i.e. relatively low) and the quality is preserved.

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3 "The Need for Independent Quality and Performance testing of Emerging Off-grid White-LED Illumination systems for Developing Countries", Evan Mills, LBNL and Arne Jacobsen, Schatz Research Center, Technical report 1, The Lumina project, August 2007, http://light.lbl.gov.

4 US DOE. "Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market". 2006.

Both the correlated colour temperature (CCT) and the colour-rendering index (CRI) vary within large intervals. A new study of colour rendering of LED sources[5] with a paired comparison of halogen and fluorescent to seven different clusters of LED at 3000K (CCT). They found, that in general, that the colour rendering was found more attractive with some of the LEDs mixing than with standard light sources. In general, alternative scales for measuring the colour rendering are discussed. The investigation finds that neither of the alternative scales for measurement of colour rendering are optimal – they all have their weak and strong points: attractiveness (Gamut is the best scale), naturalness (CRI best) and colour difference (CIECAMO2 best).

The beam characteristics of LEDs are usually determined by discrete optical elements attached to the LED or LED board. The beam and field characteristics are different from a reflector optic with a single source and this might result in a non-circular beam pattern, colour variation across the beam (especially for single LED devices) and failure to achieve good beam definition at beam angles below 24 degrees[6]. For more detailed setting of requirements to LEDs, the rated lumen output of the LED luminaire is thus important. Requirements to the manufactures could be measurement of total luminous flux e.g. by use of photo-goniometer in order to characterize the light-distribution pattern.

Formalisation of product quality and a performance testing process is needed urgently. Independent testing has to start as soon as possible and the results have to reach the key audiences. The availability of standard test procedures can support manufacturers' product development efforts, evaluation of progress towards achieving higher quality (comparison to established benchmarks) and competitive analysis. This will be taken care of in the new IEA 4E SSL annex.

On the other hand, it is important to ensure the cost of testing is not overly burdensome to manufacturers. High-cost testing can be less successful than a more moderate approach because small firms might be unable to afford the entry cost to high-cost testing and some manufacturers might avoid markets where quality assurance is required. The testing become problematic as new methods has to adapt to that LED products have such long lives that lifetime testing and acquiring of real application data on long-term performance can versions of products might be available before current ones are fully tested.

An example of lamp performance measurements including LED lamps can be found at the Renewable Energy Olino web site[7] including use of different fittings.

UV/blue light radiation and high intensity glare are identified as a potential risk factors[8] and quality requirements plus care has to be taken[9].

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5 "Colour Rendering of LED sources: Visual experiment on Difference, Fidelity and Preference", Jost-Boissard, Fontoynont and Blanc-Gonnet, Ecole Nationale Travaux Publics de l'Etat,CIE Light and Lighting Conference with emphasis on LED, 27-29 May 2009.

6 Comment from PLDA in the Eco-Design pre study concerning domestic lighting, lot 19, May 2009.

7 http://www.olino.org/

6. EU LED QUALITY CHARTER for LED lamps

1.1. SCOPE

The quality charter is a European voluntary set of requirements for **LED lamps** for use mainly in the **residential sector** as **replacement** for the phased-out incandescent lamps. The Quality Charter is **not a label** to be place on the lamp or lamp package but a set of requirements that can be used to ensure high quality in LED manufacturing, marketing, consumer awareness and confidence.

The charter could also apply to use of the products in other sectors (e.g. hotels). The requirements address products from both European and non-European manufactures.

Due to IEC/PAS 62612, point 3.1: A self-ballasted LED-lamp is a unit that cannot be dismantled without being permanently damaged, provided with a lamp cap conforming to IEC 60061-1 and incorporating a LED light source and any additional elements necessary for starting and stable operation of the light source.

A LED lamp typically include one or more packaged LED chips, a thermal heat sink to cool the chips, a housing, and a lamp cap providing connection to the electricity supply. Often a circuit driver is included. Plastic lens or bulb might be used to shape the lamp's light distribution.

1.2. SAFETY

item	minimum requirement	measurement method
Safe in use, when installed and at the end of life	Lamps must meet the safety requirements and comply with relevant CE Marking legislation	IEC 60061 IEC 62031 (2008) IEC 62471 IEC 62560 IEC 62663-1

8 European Commission Health and Consumer DG, Commitee SCENIHR: "Light Sensitivity" 26th Plenary 23/9 2008, and EU directive 2006/25/EC including photobiological hazard of visible radiation.

9 Health issues to be considered with lighting systems using LEDs (In French), ANSES, October 2010.

1.3. CONFORMITY OF PERFORMANCE

item	minimum requirement	measurement method
Conformity of Performance	The Manufacturer must provide a written conformity of performance from an approved Notified Body. If required, relevant test data must also be provided by the Body.	93/465/EEC Module A, Notified Bodies are defined in the Annex. Updated list of Notified Bodies is published in the Official Journal of the European Communities.

1.4. PERFORMANCE

item	minimum requirement	measurement method
Efficacy (including ballast)		IES LM-79-2008

	CRI	Min efficacy	2011	2012	2013	2014	2015
NDLS	>80	lm/W	61	65	70	75	80
	>90	lm/W	52	55	60	65	70
DLS	>80	lm/W	50	55	60	65	70
	>90	lm/W	40	45	50	55	60

NDLS = Non Direct Lighting Sources

DLS = Direct Lighting Sources

In the future, 2012 to 2015 targets might be revised according to the development in LED efficacy. Any revision will be discussed and approved at least 6 month before the entry into force

item	minimum requirement	measurement method
Lumen maintenance	$L_{70}F_{50} \geq 15,000$ hours Maximum 50% lamps having lumen maintenance below 70% after 15,000 hours. $L_{85}F_{05} \geq 1000$ hours Maximum 5% lamps having lumen maintenance below 85% after 1000 hours.	IEC/PAS 62612 Ed1 including a temperature cycling shock test and a supply voltage switching test with a number of cycles equal to half of the rated lamp life without any failure. IEC/PAS 62612 Ed1 testing after 1000 hours. The testing have to be performed under typical operating conditions e.g. operating in three different environments: open-air, semi-ventilated and enclosed.

Stabilised light output	The starting time shall be less than 0.5 second. The time to 95% of stabilised rated lumen output after switch-on from cold, at normal room temperature, shall be less than 2 seconds.	IES LM-79-2008 IES LM-80-2008
Colour rendering	CRI > 80	CIE No. 13.3 – 1995
Colour temperature	CCT shall be in the interval 2600 - 3500 K. The rated colour shall preferably be one of the three values: F2700 (2720K, X=0.463, Y=0.420) F3000 (2940K, X=0.440, Y=0.403) F3500 (3450K, X=0.409, Y=0.394)	IEC/PAS 62612 Ed.1. IEC 60081, Annex D.2, modified. A tolerance category of 7-step MacAdam ellipse size shall be assigned as maximum spread, that includes (circumscribes) the chromaticity co-ordinates of all LED lamps in the tested sample.
Dimensions	Directional retrofit LED lamps shall be designed physically and functionally to replace GLS and halogen reflector lamps with reference to the maximum outline specified.	IEC 60630
Glare and blue light hazard	The visible radiation hazard class shall be 0 or 1.	IEC 62471-2
Flicker	The frequency is required to be ≥100 Hz. No flicker must appear when the LED is dimmed covering all light output levels.	IEC 61000-3-11
Power factor	The power factor shall at least be 0.5 for lamps of wattage 2-25W.	IEC 61000-3-2:2006

1.5. INFORMATION ON PACKAGE

item	minimum requirement	measurement method
Lighting facts	Existing EU regulation already require to display energy class, lumen, estimated yearly energy cost, CCT, life time, wattage, warm-up time, beam angle (for directio-nal lighting sources) and a warning if the lamp can't be dimmed.	EU 98/11/EC EU 244/2009 New eco-design regulation for directional lamps coming in 2011.
Colour rendering	It is recommended that the CRI is displayed.	CIE No. 13.3 – 1995
Comparison LED/incandescent lamps	Where the packaging, or other literature claims that the rated luminous flux of the LED is equivalent to, or exceeds that, of an incandescent lamp the lamp rating must comply with existing EU regulation.	EU 244/2009 eco-design for non-directional lighting sources. New EU eco-design regulation for directional lighting sources coming in 2011.

1.6. GUARANTEE & QUALITY

item	minimum requirement	measurement method
Guarantee to customer	EU regulation already provides the customer with 2 years guarantee in case of lamp failure.	EU 1999/44/EC
Quality of production	Lamps must be manufactured under a Quality Assurance System.	EN ISO 9002 or equivalent