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Improving the Well-being of High-Arctic Residents by Modifying Light Exposure while Saving Energy

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Abstract
We conducted a lighting retrofit study at Canadian Forces Station Alert (latitude 82°30'N), the world's most northerly, permanently inhabited settlement. Existing recessed fluorescent troffers with nominally 6500K T8 lamps on electronic ballasts, providing ambient lighting in selected offices, were replaced, one-for-one, by 5000K LED luminaires. The new luminaires had higher efficacy and a high colour rendering index, and were dimmable at the room level with a wall control. A variety of well-being measures pertaining to the office occupants, and energy use data, were collected before and after the retrofit. Preliminary results suggest that, as predicted, the enhanced features of the LED system led to a generally better appraisal of the lighted environment, and substantial lighting energy savings of ~30%.

Introduction
This study was conducted at Canadian Forces Station (CFS) Alert, the world's most northerly (latitude 82°30'N, see Figure 1), permanently inhabited settlement. Energy requirements at CFS Alert are provided by diesel fuel transported via military heavy-lift aircraft. Thus energy supply is very expensive and has by-products with the potential for environmental damage in a delicate eco-system. Recently, Defence Research and Development Canada has undertaken a major energy audit and investigations of alternative power and energy technology options to reduce fossil-fuel use. Findings of the energy audit confirm that a significant portion of station electricity use is due to lighting loads (~26%).

Figure 1. CFS Alert location, and photo of the site (www.science.gc.ca 2006 Lorita On-Ice Expedition.).

The International Commission on Illumination (CIE) concluded that the lifestyle in industrialized countries does not provide adequate light exposure for optimal well-being [CIE, 2004/2009]. The residents of CFS Alert experience great extremes in natural daylight exposure at this latitude. In winter months there is no daylight availability at all, and light exposure comes only from electric lighting at typical indoor levels. Residents at extreme polar latitudes experience disrupted circadian rhythms and reduced sleep quality in winter [Arendt, 2012]. Prior work at polar latitudes has explored retrofit electric lighting technology as a solution to these problems. Francis et al. [2008] found that increasing light exposure using supplemental light boxes in occupied spaces improved sleep timing and sleep efficiency in a small sample in the Antarctic winter, and Mottram et al. [2011] found that blue-enriched fluorescent lamps instead of the Antarctic station's usual white lamps yielded benefits to sleep onset and latency. Therefore, if lighting energy use at CFS Alert is to be reduced, it is important that this not be achieved by a general reduction of light levels in occupied spaces.

In this study we tested whether a retrofit from a conventional T8 fluorescent luminaire to an LED luminaire in an office area of CFS Alert could both improve staff well-being and lower energy use. Energy reductions were expected because the chosen LED system had higher efficacy and room-level occupant-selectable dimming control [e.g. Galasiu et al., 2007]. Well-being improvements were expected because the LED system had personal dimming control [e.g. Boyce et al., 2006], higher colour rendering (CRI), and greater light output in the 460-480 nm range of the visible spectrum, to which the retinal ganglion cells which regulate circadian rhythms and influence subjective alertness are most sensitive [Lucas et al., 2014]. This study provided a rare opportunity to assess both energy and well-being effects of a lighting retrofit at such an extreme latitude.

Methods and Procedures

In November/December 2014, selected office lighting on one floor of the main administration building at CFS Alert was renovated using LED luminaires following an extensive planning and review process [Veitch et al 2015]. Other office areas had no change to the lighting, providing a control group for the well-being measures. The retrofit was a simple replacement of the old fluorescent luminaires (primarily 2-lamp 1x4) with the new, keeping locations and assignment to circuits unchanged. Dimming control for the LED luminaire was a sliding switch on the wall of each office space, replacing the previous on-off switch. Table 1 compares the old and new luminaires, and Figure 2 compares their spectral outputs. We assessed occupant well-being and lighting energy use before and after this retrofit. This paper presents preliminary analyses in both these domains.

Table 1. Comparison of existing fluorescent and new LED luminaires.

	F32T8_SP65	**LED (@100% output)**
Lumen output (lm)	3130*	4000**
Power (W)	~ 59*	44** NRC
Luminous efficacy (lm/W)	53*	92
CCT (K)	5757 NRC	5013 NRC
CRI	82 NRC	90 NRC
Illuminance (lx) @ 1.5 m	605 NRC	713 NRC

Note. *DRDC consultant report. **Manufacturer's literature. NRCMeasured at NRC with mains electricity (117 VAC).

Well-being was assessed on multiple dimensions via a survey and during an on-site visit by researchers in February 2014. The survey included items related to: environmental features and overall environmental satisfaction (including satisfaction with lighting, ventilation and acoustics); additional acoustics, thermal comfort, lighting evaluations; chronotype; sleep quality; sleep practices; overall well-being; visual and physical comfort; and, demographic information[1]. Photometric measurements were also taken. In February 2015 the survey was repeated using the same questionnaire administered on our behalf by CFS Alert personnel. Note that due to normal staff rotation, the individuals completing the survey at the two sample times were different, and thus this represents a between-subjects approach. The analysis in this paper is limited to the lighting evaluations, assessed using the Office Lighting Survey (OLS) [Eklund & Boyce, 1996].

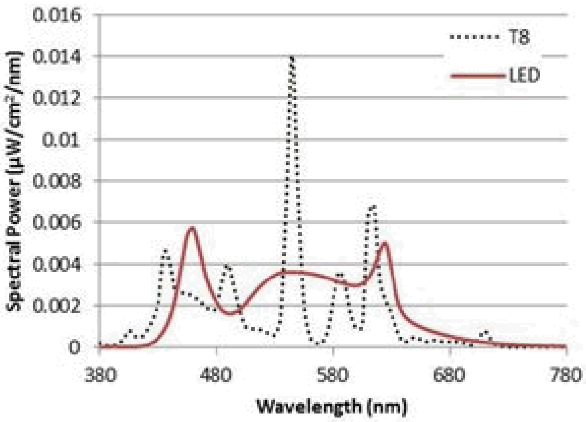

Figure 2. Spectral output of the existing T8 fluorescent lamps and LED retrofit luminaires.

Sub-metering of electricity use was already in place, and we identified a circuit of 48 luminaires[2] for which consumption data were available at 15-minute intervals from January 1st 2013 to February 28th 2015. However, the sub-metered circuit included spaces on the same floor that were not retrofitted with new luminaires, and also included additional plug loads, which diluted the effect of the LED lighting retrofit in the data. We wanted to compare data from the same season, but to avoid novelty effects associated with the new lighting. To achieve this, we looked at energy use 43 days before the retrofit, and for a 43-day period after the retrofit but also after a three-week settling-in period. Rather than examine total energy use, we attempted to filter out lighting from other end-uses by looking at the daily difference between the median use during the occupied, daytime period (noon-9pm) and the inactive overnight period (midnight-6am), which emphasized loads triggered by daytime staff occupancy hours (e.g. lighting) and not loads that ran 24 hours per day (e.g. refrigeration and some office equipment). For the same reason, we excluded weekends and public holidays from the analysis. We used a simple *t-test* on this "daily rise" metric to determine statistical significance of any change post-retrofit.

Results

Table 2 shows responses from the OLS comparing normative data and the samples from the two administrations at CFS Alert.

Figure 3 shows energy data from the sub-metered circuit in the study area. Weekly and diurnal patterns in energy use are clear, as is the general reduction in peak daily energy use and the daily rise metric post-retrofit. The t-test shows a statistically significant reduction in the daily rise metric of 30% post-retrofit (t_{81}=10.3, p <0.001), equivalent to an average reduction of 28 W per luminaire. The LED luminaires at full output used 15 W less than the fluorescent luminaires, therefore, the results suggest that the manual dimmers were being used at approximately 70 % of full output, on average[3].

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[1] We also conducted experience sampling, which combined measurements of light exposure made continuously by a light monitor on a wristwatch-like device with questions answered on a handheld computer, over a two-day period for each participant. The questionnaire measures were: current experiences (hourly, 08:00 to 21:00); daily sleep diary (each morning); and, demographics. These data are not reported here.

[2] 44 of these were in the study offices, and 4 in an adjoining corridor on the same electrical circuit.

[3] We assume all 48 fixtures contribute to this reduction. It is possible that some luminaires were in spaces used for storage, contributing little to the saving and raising the savings contribution of the luminaires in active office

Table 2. OLS responses. Upper section (Q1-9) shows % agreeing with each statement; lower section (Q10) shows % of responses in each category. "Norm"= normative data, a mid-1990s sample in northeastern United States. FL=respondents with conventional fluorescent lighting in their office; LED=respondents with retrofit LED lighting system in their office.

	Norm	CFS Alert		
		2014	2015	
		FL (N=28)	LED (N=11)	FL (N=8)
1. Overall, the lighting is comfortable.	69	86	100	75
2. The lighting is uncomfortably bright for the tasks …	16	22	9	13
3. The lighting is uncomfortably dim for the tasks that I perform.	14	11	0	0
4. The lighting is poorly distributed here.	25	18	9	13
5. The lighting causes deep shadows.	15	7	9	13
6. Reflections from the light fixtures hinder my work.	19	7	9	0
7. The light fixtures are too bright.	14	18	18	25
8. My skin is an unnatural tone under the lighting.	9	4	0	38
9. The lights flicker throughout the day.	4	7	9	38

10. How does the lighting compare to similar workplaces in other buildings?			Worse	Same	Better
Norm			19	60	22
CFS Alert	2014	FL (N=27)	11	78	11
	2015	LED (N=11)		45	55
		FL (N=8)		100	

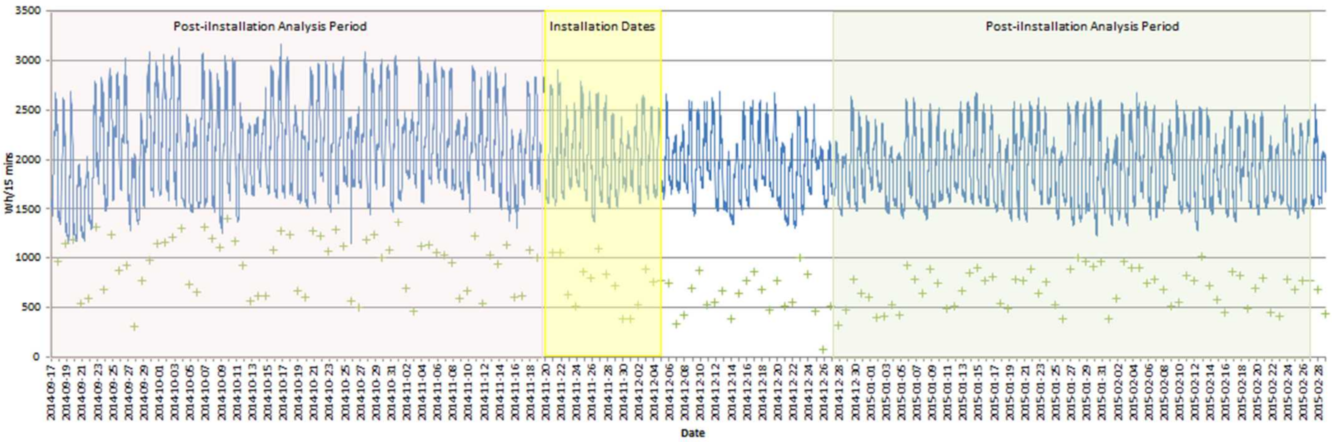

Figure 3. Seven months of energy data for the sub-metered circuit with 48 LED luminaires. The blue line shows 15-minute total energy use data (circuit included other loads), the green markers show daily rise metric used for statistical analysis. Date ranges used in statistical analysis are shown (note, only normal weekday values in these ranges were used).

Discussion

The OLS sample is relatively small, nevertheless, the results in Table 2 present a consistent pattern. The office workers at CFS Alert experiencing fluorescent lighting report similar evaluations to the normative sample (who were primarily office workers with conventional fluorescent lighting): overall ratings were higher for the fluorescent lighting occupants at CFS Alert, but ratings related to brightness were lower. Ratings from office workers with the new retrofit LED lighting were generally superior to both years of ratings for fluorescent lighting, with the better ratings for bright/dim characteristics as might be

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spaces. Photographs taken several months later confirm some dimmer usage. Nevertheless, changes in personnel, duties, practices and other loads cannot be entirely accounted for in the analysis.

expected with a system that affords a level of personalized dimming control. Ratings for the fluorescent luminaires for skin tone and flicker were substantially worse in 2015 compared to the same system in 2014. This might be explained by the existence in 2015 of the LED lighting system (with its higher CRI), which may have presented an informal comparison condition. However, the difference might also have been due to the different perceptions of the different individuals performing the ratings at the two measurement periods; such biases may be more obvious with a small sample size. Formal statistical analyses of these outcomes, and others in the survey package, are planned to further investigate whether the LED system was effective in improving aspects of well-being.

The expected energy benefits of the new lighting system were observed. Analysis of energy use data from another sub-metered circuit receiving 16 retrofit luminaires corroborated this finding.

Conclusions

A lighting retrofit at CFS Alert, from conventional fluorescent to dimmable LED ambient office lighting, demonstrated benefits on lighting quality evaluations and yielded substantial energy savings. Although based on a small sample (as is inevitable at such a high latitude) the results suggest that occupant well-being and energy savings can be mutually compatible in a well-designed retrofit. Subsequent additional analyses are planned to reinforce these findings. Both the light exposure regime and the cost and environmental effects of wasted energy were extreme in this location, but if similar effects persisted at more populated, lower latitudes, even if these effects were diluted in the more moderate circumstances, the overall societal benefits would be substantial.

Acknowledgements

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