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Investigation of an integrated automated blinds and dimmable lighting system for tropical climate in a rotatable testbed facility

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ABSTRACT

Performance of automated blinds and auto-dimming lighting system in providing lighting energy savings and occupant visual comfort was studied in a rotatable testbed facility located in tropical Singapore. The automated Venetian blinds system, consisting of a daylight-redirecting top portion and a glare-controlling bottom portion, was controlled by an in-house developed control algorithm designed specifically for tropical climate of Singapore to introduce maximum daylight while minimising Daylight Glare Probability (DGP). The auto-dimming lighting system used Digital Addressable Lighting Interface (DALI) controller to control T5 fluorescent and LED luminaries. Energy consumption by the lighting system, working plane illumination distribution and DGP were monitored by a network of sensors and high-dynamic range (HDR) camera systems. Compared to non-dimmable T5 lighting, LED lamps provided about 24% of lighting energy savings. Auto-dimming technology showed

about 46% lighting energy savings. LED lamps coupled with auto-dimming showed around 80% lighting energy savings. Without window blinds, the working plane illuminance exceeded the recommended 3000 lux level during certain time of the day and DGP exceeded 0.35. The automated blinds effectively eliminated glare discomfort, and with the automated blinds working in conjunction with the auto-dimming, significant lighting energy savings was achieved without compromising the illuminance level at the working plane. 75% of lighting energy savings was achieved for North orientation and 63% for East orientation. Façade orientation was found to have a significant impact on the lighting energy savings potential, with the North orientation achieving higher daylight savings due to higher daylight redirection possibility throughout the day. The lighting energy savings potential is higher for clearer sky conditions due to higher daylight availability. Implementation of daylight re-directing shading system has significant lighting energy savings in the tropics. These lighting energy savings can be captured by deploying an auto-dimming system. With careful design of the system and control algorithm, the lighting energy savings can be achieved while maintaining good visual comfort.

Keywords: Lighting; Energy-efficiency; Automated blinds; DALI system; Daylighting

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1. INTRODUCTION

Buildings account for about 40% of the total global energy consumption, and among various energy uses in buildings, lighting uses about 19% of the global building electricity consumption [1]. In Singapore, up to 31% of the nation's electricity is consumed by the building sector, and lighting accounts for 15% of the total building electricity consumption [2]. This indicates the significance of energy efficiency of the built environment in Singapore. Research and development of energy-efficient lighting and daylighting solutions for building provides substantial potential for enhancing building energy efficiency.

Integrated daylighting system with auto-dimming lighting is emerging as an effective green building technology due to its energy-saving and visual comfort potentials. Studies conducted in various climates have shown that significant lighting energy savings can be achieved using auto-dimming system when sufficient daylighting is available [3]-[7]. Galasiu et al. [4] reported 50-60% lighting energy savings under clear sky with lighting auto-dimming system, compared to lights fully on from 6 AM to 6 PM from field measurement in Ottawa, Canada. Fernandes et al. [5] found that daylighting-based dimming controls integrated with working plane illuminance set point tuning can result in about 20% of lighting energy savings for daylight zones in the New York Times Headquarters Building, compared to the recommended 12 W/m² lighting power density in ASHRAE 90.1-2007 [6]. Delvaeye et al. [7] reported 46% of lighting energy savings using an open loop system with Digitally Addressable Lighting Interface (DALI) control based on a one-year measurement conducted in a classroom in Belgium. In these above-mentioned studies, either T5 or T8 fluorescent lamps were used. More energy savings could be achieved by switching from fluorescent lighting to LED lighting as some studies showed [8]-[9]. A study conducted in an eight-story office building in the UK [8] reported 30% of electricity savings due to replacement of T5 lighting with LED lighting and

upgraded BMS system. Richman et al. [9] conducted a laboratory evaluation of LED and T8 lamp products. They found that 3 – 24% of lighting energy savings can be achieved by LED on different fixture types, compared to T8.

Internal shading such as manual blinds is commonly used in commercial buildings in Singapore [10]. However, oftentimes blinds are drawn down or closed once glare has been perceived and are then left in the same position throughout the rest of the day. This practice limits the daylighting potential, and increases the reliance of indoor lighting to provide the desired level of indoor illumination [10]-[11]. Automated blind systems which dynamically adjust the blind positions during the day according to daylight condition can maximise the daylighting potential [10]. Indoor lighting and blinds systems may operate independently or as an integrated system. Integrating window blinds system with dimmable indoor lighting system for indoor illumination control is, in fact, gaining attention [11][10]-[17] as an emerging solution for energy savings and enhanced indoor comfort. Lee et al. [12] experimentally studied an integrated system with automated Venetian blinds and T8 dimmable lighting in two unoccupied, private offices with Southeast-facing façade in Oakland, California. They reported that 1 – 22% daily lighting energy savings can be achieved by the integrated system, compared to a reference system with manual blinds having slats fixed at 15° and auto-dimming lighting. The same integrated system achieved daily lighting energy savings of 22 – 86% compared to another reference system with manual blinds and non-dimmable lighting. Lee et al. [13] conducted another experimental study in an 88.4-m² window system testbed facility located at Lawrence Berkeley National Laboratory (LBNL). They reported that 69% of lighting energy savings can be achieved by a system consisting of automated daylight-redirecting blinds plus auto-dimming lighting, comparing to a system with manually-operated Venetian blind and non-dimmable lighting for 6 am – 6 pm daily. Mettananta & Chaiwiwatworakul [14] reported that

more than 24% of lighting energy savings was obtained by a system consisting of auto-dimming lighting and automatic vertical blinds, compared to a base case with artificial lighting fully on, in a laboratory room with North-west facing façade in Thailand. Chaiwiwatworakul et al. [15] indicated that 80% of the lighting energy savings could be achieved with an automated blinds system and an auto-dimming ballast lighting system in an office building in Thailand. It can be seen from these previous studies that lighting energy savings by daylight-responsive auto-dimming and automated blinds system can be largely affected by daylight availability due to different location and orientation [11] -[20]. A number of numerical studies [21]-[24] also suggest that the energy saving potential of auto-dimming and automated shading systems depends on daylight availability.

The different conditions of test environment in different studies could also lead to non-repeatability in findings. Experimental studies on energy savings of lighting, auto-dimming and shading system were either estimated by comparing with benchmark code, such as ASHRAE [5], or with data obtained from other studies conducted in different locations [11]-[20], or with historical trending data [8] obtained in the same site (before-and-after type study). A side-by-side comparison would be the most ideal method for such study since both setups are exposed to the same climate conditions at the same time. So far, there is no comprehensive experimental study that quantifies the lighting energy savings and visual comfort performance for integrated auto-dimming and shading system in the tropical climate of Singapore.

The aim of this study is to experimentally investigate the performance of an integrated auto-dimming lighting and automated blinds system in the tropical climate of Singapore. A rotatable outdoor test bed facility (BCA SkyLab) was utilised to provide a side-by-side comparison setting for this study. The results shall provide new insights into the operational characteristics

and energy savings potentials of an integrated auto-dimming lighting and automated blind system in the tropical context. The current study focuses on the investigation of lighting energy savings. The impacts of different lighting and day-lighting systems on air-conditioning energy consumption will be discussed in up-coming studies.

2. EXPERIMENTAL METHOD

2.1. BCA SkyLab Test Bed Facility

The BCA SkyLab facility (as shown in Figure 1) is located at the BCA Academy, Singapore (latitude 1° 17' N, longitude 103° 51' E). The facility is situated at the roof top of a 7-storey-tall building to avoid shadow casted by neighbouring buildings. It is constructed on an outdoor 360° rotatable platform enabling tests to be carried out at any orientation under the exposure to real weather conditions. The facility consists of two side-by-side configurable test compartments (the Reference Cell and the Test Cell) and a control room located behind the test compartments, as shown in Figure 2. The two test compartments are identical in dimensions (8.41 m L × 5.54 m W × 3.47 m H), orientation and internal fit-outs, which simulates typical office environment. Such twin-test-compartment configuration facilitates well-controlled, side-by-side comparative studies. Technology/system that is being evaluated will be installed in the Test Cell which will be compared against a reference setup (usually the more conventional counterpart of the technology/system) installed in the Reference Cell. The control room houses the building management system (BMS), data acquisition system (DAQ) and the equipment for other monitoring systems. SkyLab was developed in collaboration with Lawrence Berkeley National Laboratory (LBNL) drawing reference to the concepts of FLEXLAB® [25] in LBNL. SkyLab enables controlled laboratory studies of building systems and occupant comfort, similar to those reported in [25] - [29].

SkyLab has 0.257-m-thick exterior walls, which are built up of gypsum firestop plasterboards, rock wool insulations and aluminium composite panel in powder coated finish (external cladding). One side of the compartments is fitted with full-height window façades. Each of the window façades is made of double-pane, low-E (low emissivity) glazing with aluminium frame having internal thermal block insulation. The roof is made of 100-mm-thick concrete composite decking system with 50-mm-thick ultra-foam insulation below it. The internal partition walls are 0.2-m thick, built up of gypsum firestop plasterboards in white paint finish as outer layers, with rock wool insulation and gypsum plasterboards inlays. The false ceiling, made up of 0.6 m L $\times$ 0.6 m W perforated aluminium clip-in tiles with powder-coated finish, is 0.78 m below the structural ceiling. The total solar reflectance of the internal surfaces of the walls is 0.82 and that of the false ceiling tiles is 0.60. The finished floor consists of carpet tiles covering a raised floor made from 40-mm-thick, 0.6 m $\times$ 0.6 m panels made from steel sheet surface filled with non-combustible material. It creates a void of 0.34 m high from the 25-mm-thick closed cell insulation lined floor. Internal head room (finished floor to false ceiling tile) in each cell is 3.47 m.

On the partition wall between the two cells and the control room, there is an observation window and a door on each side. Each window is made up of 2.08 m L $\times$ 1.40 m W low-E (low emissivity) double pane glazing. Each door (2.40 m L $\times$ 1.20 m W) is made up of hardwood timber and plywood on outer layer (both sides) in white paint finish. Figure 2 shows the schematics of the experimental setup. There are 4 typical office work stations (L shaped 2.0 m L $\times$ 1.6 m W $\times$ 0.73 m H) in each cell. A thermal dummy of 0.3 m in diameter and 1.1 m tall made from galvanised steel sheet with heating elements inside (constructed according to BS EN 14240 [30]) is put at the seat position of each work station. Each can provide up to 180 W

of sensible heat, adjustable according to experimental needs. Both cells are air-conditioned with room air temperature set point of 22°C and design indoor relative humidity (RH) range $\leq$ 65%.

2.2. Lighting System

Each cell is fitted with 8 lighting fixtures at the false ceiling. Each fixture has a face dimension of 0.60 m (L) and 0.60 m (W). Two representative types of lighting are covered in this study: T5 fluorescent lamp (PHILIPS TBS460 3×TL5-14W HFS D6) and LED (PHILIPS RC600B-40S L60×L60). The measured electrical power drawn by each lighting fixture was 51.75 W (T5) and 46.00 W (LED), at their respective maximum outputs. The lighting power density per unit floor area in the cells was 7.9 W/m² for T5 and 6.1 W/m² for LED.

Different lighting control systems including occupancy-based, daylight-responsive-based, time-scheduling-based or mixed mode were developed to implement auto-dimming [31]. In buildings with adequate daylight availability, control systems that are daylight-responsive-based can provide maximum lighting energy savings [31]. The commercial DALI (Lutron) control system installed in SkyLab utilizes a centralized lighting control system similar to that described in [32]. A ceiling mounted daylight sensor, as shown in Figure 2, detects the daylight illuminance conditions and provides control feedback to the central controller. The central controller then determines and controls the dimming levels for each lighting zone. The 8 lighting fixtures in each cell are divided into 4 zones, as shown in Figure 2. Zone 1 and zone 2 (or the inner zones), are individually controlled. Zone 3 and zone 4 are controlled together as one zone (or the perimeter zone).

An illumination distribution test was carried out in both cells with all lighting fixtures set to 100% output based on the procedures in IESNA [33]. The test was conducted at night time with all windows blocked by cardboard papers to minimize external disturbances. Illuminance measurements in each cell were made in a pre-defined grid of measurement points with 1.07 m $\times$ 1.07 m grid size covering the horizontal cross section of the entire cell, i.e., 8 points length-wise and 5 points width-wise (total $8 \times 5 = 40$ measurement points), at the working plane height (height of work desk table top, 0.73 m above the finished floor) as shown in Figure 2. The grid size in the row furthest away from window façade, is 1.07 m $\times$ 0.73 m. Measurements were conducted using a portable handheld lux meter (Tenmars TM 202 Lux/FC, accuracy $\pm 3\%$ of reading - calibrated against standard incandescent lamp 2,856 K / $\pm 6\%$ of reading - other visible light source). The sensor of the lux meter was placed on a horizontal plate mounted on top of a 0.73-m-tall pedestal to represent working plane level height. Levelling of the sensor was checked by bubble-level. At the centre of each grid point, three spot measurements of illuminance level were repeated. The sensor was rested at the measurement point for 1 minute for the reading to stabilize before each spot measurement was taken. Three repeats of spot measurements at each grid point took approximately 5 minutes in total.

The illumination distribution test was conducted once with T5 lamps and once with LED lamps. The average horizontal illuminance level at working plane height was 540.8 Lux with T5 lamps and was 538.9 Lux with LED. It is in compliance with the recommendation of above 500 Lux at the working plane in SS531: Part1: 2006 [34]. The uniformity of illuminance in the task area (the parts where the desks are located) was above 0.7 and above 0.5 in the immediate surrounding area (a zone of at least 2 m width surrounding the task area within the field of vision), complying to the recommendation in SS531: Part1: 2006 [34]. The uniformity of illuminance is defined as the ratio of the minimum value to the average value of illuminance.

2.3. Window Blinds Systems

Full-height manual Venetian blinds consisting of white matte-finish slats (25 mm wide, total solar reflectance: 0.56) is installed inside of the window façade of Reference cell. The slat angles of the manual blinds system was set at a pre-defined position (close/open/retracted) manually depending on experimental need. The total solar reflectance of the blinds slats were measured by a portable solar spectrum reflectometer (Devices & Services, SSR-ER version 6).

In the Test cell, Venetian automated blinds, which are divided into two sections as indicated in Figure 3, are installed. The upper one-quarter-height portion (or the daylight re-directing section) is made up of mirror-finish top surface daylight-redirecting slats (50 mm wide, total solar reflectance: 0.91). The lower three-quarter-height portion (or the glare controlling section) comprises of white matte-finish slats with same properties as those in the Reference cell.

An in-house developed control algorithm was implemented to control the slat angles of the automated blinds in the Test cell with two main objectives – 1. Control glare and 2. Maximise the daylight penetration to the room. The control algorithm determined the slat angles of the lower portion of the blinds such that the Daylight Glare Probability (DGP) [26] at a reference point in the cell will never exceed 0.35 (threshold for perceptible glare) [35] and the slat angles of the upper portion to allow maximum daylight penetration into the cell. A constraint of not exceeding the maximum threshold of 3,000 Lux of working plane illuminance, recommended in [36], was imposed. The algorithm is implemented through the test bed's building management system (BMS) which also takes the real-time sky conditions and façade orientation inputs. The control system directs the motor of the automated venetian blinds to

change the slat angles every minute. The flowchart of this control system is shown in Figure 4. The control algorithm was developed based on the results obtained by RADIANCE [37] simulations using Singapore weather condition and different window orientations as inputs. Existing automated blinds control algorithms are either developed for temperate climate [13] or lacking daylight re-direction capabilities [15]. In the control algorithm, DGP was chosen as the index for visual comfort since Suk et al. [38] suggested that DGP shows the best evaluation performance compared to other indices. Further discussion about different visual comfort indices is given in Section 4.2.

A typical profile of the automated blinds and its successful control of working plane illuminance and DGP at the reference point is shown for two orientations (North and West) in Figure 5 and Figure 6 respectively. The reference point was located at the middle point between the two work stations closest to the window façade, indicated in Fig. 2(a) as “HDR camera”. The high dynamic range (HDR) camera was mounted at 1.7 m height from the floor with its lens pointing perpendicularly towards the window façade. During the development of control algorithm, the results for two heights (seating = 1.1 m and standing = 1.7 m) were evaluated and 1.7 m position was found to have higher frequency of disturbing/perceptible glare. Hence, 1.7 m was chosen as the reference point for blinds controls as a conservative approach towards visual comfort. For working plane illuminance, 0.7 m was the reference height.

2.4. Instrumentation

In each cell, horizontal illuminance at working plane height was measured by 8 illuminance sensors. The 4 illuminance sensors in zone 1 and 2 (inner zones) are having a measurement range of 0-10,000 lux (KIMO LR-110 PN, accuracy $\pm 3\%$ of reading) and the other 4 located in zone 3 and 4 (perimeter zone) are having a measurement range of 0-150,000 lux

(REINHARDT light intensity sensor, accuracy $\pm 6\%$ of reading). Each illuminance sensor was mounted on pedestals with bubble level. An extra illuminance sensor (REINHARDT light intensity sensor, accuracy $\pm 6\%$ of reading) was placed on the rooftop to measure the outdoor horizontal illuminance. Lighting electrical power drawn by each lighting zone (two lighting fixtures per zone) was monitored by a power meter (PowerLogic iEM3155, active energy accuracy $\pm 1\%$ of reading). All illuminance sensors and power meters were reading and data-logging at 1-min intervals through the central DAQ system (National Instruments) of SkyLab. Besides being factory-calibrated, all the sensors and instrumentations had gone through systematic site verification.

Glare in the test cell was measured using a HDR camera setup. The HDR imaging system consists of a camera (Canon 70D) equipped with memory card and a power adaptor for continuous power supply. The camera was mounted with a fisheye lens (Sigma 4.5 mm F/2.8 EX DC HSM) for 180° circular imagery. The camera-lens set was mounted on a tripod with bubble level. A photometric sensor (LICOR LI-210R, accuracy $\pm 5\%$) was mounted on top of the camera and facing the same direction of the camera. Data acquisition for the photometric sensor was facilitated through a data acquisition module (LabJack U3-HV) and was transferred to a compact computer (Mac Mini). The compact computer was installed with the required software to control the image capture and perform image processing and finally glare analysis. The overall process of DGP measurement was controlled using multiple programs through a main script written in Bash (Bourne Again Shell) command language. The main script ran every five minutes to collect the photometric sensor data, capture raw HDR images, calibrate these images with the photometric sensor illuminance data, apply vignette correction, analyse glare of the calibrated HDR image using the Evalglare software and finally generate false colour image illustrating the DGP values.

2.5. Experimental Setup

Seven tests (Table 1) were designed to study the performances of lightings, auto-dimming system, automated blinds system and the integrated system. Each test ran from 9:00 am - 6:00 pm per day, following the typical office working schedule, for three days apart from Test 1 which ran for two days. For ease of comparison, three-day normalised results are presented for Test 1. All tests were conducted in the period of May 2016 - May 2017. In Singapore, buildings are recommended to minimize façade exposure to the East and West orientations [10] and, thus, the North represents a typical façade orientation setting in Singapore. Test 1 was conducted as a baseline test to compare the energy savings of having LED lighting (Test cell) compared to T5 lighting (Reference cell) without any influences from auto-dimming control and window blinds. Test 2 and Test 3 were conducted with blinds retracted to isolate the lighting energy savings potential of the auto-dimming system and the LED lighting. Test 4 was designed to explore the lighting energy savings contribution just from the automated blinds and Test 5 was designed to check the further contribution of auto-dimming and automated blinds. Both these tests were conducted with T5 lighting and North-facing window façade. Test 6 and Test 7 studied the integrated system consisting of auto-dimming lighting and automated blinds. Test 7 had the same settings as Test 6 except that the façade orientation was changed to East, by rotating SkyLab, to investigate the impacts of orientation on energy savings potential of the integrated system.

The sky condition was evaluated using clearness index (K_t). K_t is defined as the ratio of the global horizontal irradiance to the extra-terrestrial irradiance [39]. A roof top sensor (Delta T devices SPN1, accuracy $\pm 5\%$) measured the global horizontal irradiance and extra-terrestrial radiation was calculated for all time stamps during the experiment. $K_t \geq 0.65$ was classified as

clear, $0.2 \leq K_t < 0.65$ was classified as intermediate sky and $K_t < 0.2$ as overcast sky [40]. Table 1 shows the K_t for all experiment days.

3. RESULTS

3.1 Lighting energy

3.1.1 Lighting energy savings by auto-dimming

Table 2 summarises the lighting energy consumption (in kWh) in each test. Figure 7 shows the comparison of lighting energy savings of all the tested technologies with respect to a common reference baseline, i.e., T5 fluorescent lamps, no auto-dimming and retracted blinds (Test 1 – Reference Cell).

Test 1 shows that about 24% of lighting energy can be saved by using LED lighting when compared to T5 lighting. Both lighting systems are running at their maximum output throughout the day (9 am – 6 pm). This saving was achieved under the condition that both lightings complied with the recommended minimum horizontal illumination and uniformity at the working plane, as described in Section 2.2.

In Test 2, about 47% of lighting energy savings was achieved by the auto-dimming system when both cells were using T5 lighting, as shown in Table 2. A similar level of lighting energy saving is observed in Figure 7, when Test 2 – Test Cell is compared to Test 1 – Ref Cell. Test 3 shows that by adding the auto-dimming function to LED, it achieved about 42% more lighting energy savings than adding auto-dimming to T5 lighting. It suggests that the energy benefit of auto-dimming is more prominent in LED compared to T5 florescent lamps. This could be due to the difference in dimming effects between LED and T5 as the two types of lamp have

different lighting efficacy. As shown in Figure 7, the LED with auto-dimming saved about 80% lighting energy compared to the base case of T5 fluorescent lamps with no auto-dimming.

Although significant lighting energy savings are observed in Test 2 and 3, visual comfort was compromised at certain time of the day due to over-illumination and glare. This could be due to the fact that the blinds were retracted in these two tests. Visual comfort will be discussed in more detail in Section 3.4.

3.1.2 Lighting energy savings by integrated auto-dimming and automated blinds system

Test 4 show that the automated blinds system led to about 30% (Table 2) of lighting energy savings by utilizing daylighting, compared to keeping the blinds closed throughout the day. Both the cells had auto-dimming and T5 lamps in this test. Taking out the auto-dimming function and letting the T5 lamps to run at full power in the Reference cell, the integrated auto-dimming and automated blinds system in the Test cell provided about 57% of lighting energy savings (Test 5), comparatively. Switching the T5 lamps to LED lamps in the Test cell (Test 6), the lighting energy savings can be further enhanced to about 74%, compared to the same Reference cell setting. Similar results are observed in Figure 7 where the base case is the common reference.

3.1.3 Effect of sky condition on lighting power

Figure 8 shows the relation between sky condition and lighting power for tests with retracted blinds or automated blinds (excluding closed blinds). There is an observable trend of lower lighting power (more lighting energy savings) as the sky condition becomes clearer, when auto-dimming is adopted. In general, more energy savings can be achieved by auto-dimming when the blinds are retracted compared to automated blinds. This is particularly prominent at sky

conditions with high clearness index. The subsequent impact on visual comfort will be discussing in the next section. With T5 lighting, in the perimeter zone, the lighting power was auto-dimmed to zero power (fully rely on daylighting) for most of the time when the clearness index was above 0.3 if the blinds were retracted, as shown in Figure 8(c). Lighting was needed for more time if automated blinds were used due to the shading effect provided by the automated blinds. No lighting was needed when the sky condition was Clear, for both retracted and automated blinds. When LED lighting was used, lighting power was auto-dimmed to zero for the majority of time for Intermediate and Clear sky conditions (Figure 8 (d)). Higher levels of dimming can also be observed in the Overcast sky condition compared to T5 lighting, indicating a higher lighting efficacy of LED.

3.1.4 Impact of façade orientation on lighting energy savings

The impact of facade orientation is examined by comparing the results of Test 6 and Test 7. For facade facing East (Test 7), the same setup resulted in about 63% lighting energy savings, compared to 74% with façade facing North (Test 6). Figure 9 (a) and Figure 9 (b) shows the difference in the lighting energy consumption for the inner and perimeter zones, respectively, in both orientations. The Test cell consumed significantly more lighting energy with East-facing façade than North-facing, suggesting that the East façade orientation has less daylight availability (or potential for dimming) than the North orientation. This could be due to the fact that although there is ample amount of daylight available in the morning in the East orientation, the East-facing façade is under the shadow of the SkyLab itself in the afternoon and, thus, less daylight redirecting potential compared to North on a daily basis. This was further verified using ECOTECT [41] simulation for different times of the day on summer solstice. This is finally reflected in the system's ability to save lighting energy consumption.

3.2 Visual comfort

3.2.1 Working plane horizontal illuminance

At full output, LED lamps achieved equal or higher working plane horizontal illuminance compared to T5 fluorescent lamps, as shown in Figure 10 (a) (Test 1). Similar observation can be seen in other tests (see Annexure).

In the cases of Retracted blinds, the working plane horizontal illuminance exceeded the recommended level of 3000 Lux [36] in Zone 4, which is at the close proximity to the window façade, with abundant daylight (see Figure 10 (b)). The sky became Overcast after 15:10 on the day of experiment. Auto-dimming helped to reduce the excessive horizontal illuminance found in Zone 4 but it was not able to control the illuminance levels down to the recommended range of below 3000 Lux (see Figure 10 (c)).

For Closed blinds cases, the working plane horizontal illuminance had never exceeded the 3000 Lux level in the perimeter zones (see Figure 10 (d)). However, keeping the blinds closed throughout the day to avoid over illuminance in the perimeter zones also largely hampered the lighting energy saving potential of auto-dimming. In Table 2, comparison between the lighting energy consumption of Test 4 Reference cell (9.36 kWh) and Test 5 Reference cell (10.70 kWh) shows that lighting energy savings by auto-dimming under the closed blinds condition was minimal.

For Automated blinds, the working plane horizontal illuminance levels also complies with the recommendation of below 3000 Lux for 90% of occupied hours (Figure 10 (c)). However, Automated blinds allowed for higher potential for auto-dimming compared to Closed blinds. As discussed earlier, the Automated blinds led to about 30% of lighting energy savings (Test

4 – Test Cell), while keeping the working plane horizontal illumination level within the recommended levels.

The sky condition also has an impact on the working plane horizontal illuminance. Figures 11 (a) – 11 (d) show that Retracted blinds led to higher variance in working plane horizontal illuminance than Automated blinds in each of the respective sky condition category. This is particularly obvious in the perimeter zones. It suggests that the automated blinds may reduce the annoyance due to high variance in illuminance level to the occupants. Across different sky conditions, the trends of increasing working plane horizontal illuminance with sky clearness index are observable in both the Automated and Retracted blinds cases. The variation of working plane horizontal illuminance across different sky conditions was much less with Automated blinds than that with Retracted blinds. It indicates that the Automated blinds stabilised the working plane horizontal illuminance when for different sky conditions.

3.2.2 Glare

Figure 12 shows the statistics of measured DGP under different combinations of lighting and blinds setting. For Retracted blinds cases, the majority of the daytime was having DGP higher than 0.35, threshold for perceptible glare [35]. Specifically, when the sky condition was Clear, more than half of the time the DGP was either disturbing or even intolerable. When the sky condition was Intermediate, nearly half of the time the DGP was disturbing or worse.

For cases with Automated blinds, DGP was kept below 0.35 at all times. This indicates that the automated blinds were effective in controlling glare. There is an observable trend that DGP increased as the sky condition went clearer. This could be caused by the automated blinds which were programmed to bring in as much daylight as possible, within the visual comfort

criteria. As expected, the Closed blinds maintain the DGP below 0.35 in the imperceptible range for all sky conditions.

3.2.3 Façade orientation effect

The integrated system with LED lamps maintains the working plane horizontal illuminance within the recommended 500 lux and 3000 lux at all zones in both North and East orientations, as shown in Figures 13 (a) and 13 (b). It was also able to control the DGP below 0.35, as shown in Figure 14 for both orientations. It should be noted that when the window façade was facing East, strong daylight could be present in the morning time. There is no major variation of working plane horizontal illuminance level and DGP across different sky conditions. It can be summarised that visual comfort is maintained satisfactorily in both orientations by the integrated system.

4. DISCUSSION

4.1 Limitations on experiment duration

The testing duration for each test listed in Table 1 was for one week, out of which results for three days of similar weather condition (intermediate sky condition) were taken out for analysis and comparisons in this paper. Although the tests were run at different months, which have different solar altitudes, they are compared according to clearness index. This was done to ensure the comparability between different tests. Intermediate sky condition was chosen as the representative weather condition on the basis that the majority of the days in the typical metrological year (TMY) of Singapore fall into this sky condition category (see Figure 13). However, the energy savings results obtained from the three-day measurement may not be representative to the whole-year energy savings. In order to address this limitation, annual energy simulation was performed on a calibrated model of Skylab using energy modelling

software (EnergyPlus [42]). The model was set up as discussed in [43]. Figure 16 shows the comparison of the experimental results and simulation results for the combined system. Both the results are found within 10% of each other.

4.2 DGP as glare metric

Different glare metrics are recommended by different performance measurement protocol agencies, for example - DGI is recommended by the International Energy Agency Solar Heating and Cooling Program Task 21 daylighting performance monitoring procedures to assess visual comfort in daylit spaces [44] and Unified Glare Rating (UGR) by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers Performance Measurement Protocols (ASHRAE PMP) [45]. Some field studies with human subjects suggest that glare metrics like DGI, UGR and DGP are not as effective as other discomfort indicators based on luminance [46], [47]. However, in controlled laboratory tests, DGP was found to perform substantially better than other glare metrics [26]. Recent validation study [38] indicates that DGP shows the best evaluation performance amongst other five glare indices (DGI, UGR, Cornell Glare Index (CGI), Visual Comfort Probability (VCP)) when subjective evaluations are used as a baseline. Thus DGP was used as a glare metric in the current study despite its potential limitations.

5. CONCLUSION

This study investigates the lighting energy performance and visual comfort of several lighting and daylighting technologies, including LED lighting, auto-dimming and automated blinds in a rotatable test facility, BCA SkyLab, in Singapore. Compared to the common reference system consisting of non-dimmable T5 fluorescent lamps without window blinds, adding auto-dimming function showed about 46% savings in lighting energy consumption, switching to

LED lamps provided about 24% of lighting energy savings, LED lamps combined with auto-dimming showed around 80% energy savings for North orientation. These savings were obtained without window blinds, due to which, visual comfort was frequently compromised in terms of high working plane level illuminance and glare experienced by the occupants.

Compared to the same reference, an integrated system consisting of LED lamps, auto-dimming lighting control and automated blinds achieves up to 75% of lighting energy savings for North orientation. The North orientation had higher daylight savings potential due to higher daylighting potential throughout the day compared to the East orientation, which saved 63% lighting energy instead. The lighting energy savings potential is higher for clearer sky conditions due to higher daylighting potential.

Based on the results of this study following learnings can be surmised:

1. Implementation of daylight re-directing shading system has significant lighting energy savings in the tropics. These lighting energy savings can be captured by deploying an auto-dimming system.
2. With careful design of the system and control algorithm, the lighting energy savings can be achieved while maintaining good visual comfort.
3. Façade orientation has a significant impact on the lighting energy savings potential of these systems, therefore the test method should include tests in different orientations.

To summarise, in Singapore's tropical climate, the integrated system shows excellent capability to provide visual comfort while achieving significant lighting energy savings. Future work will include evaluating performance of the integrated system in terms of its impacts on thermal comfort and total building energy consumption.

474

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Figure 1: Exterior view of the BCA SkyLab

Legend:	
	Indoor illuminance sensor (Reinhardt)
	Indoor illuminance sensor (LR-110 PN)
	Thermal dummy
	HDR camera for glare measurement
	Supply air duct
	Return air grill
	Power logger
	Auto dimming control sensor
	Lighting fixture
	Thermostat

Figure 2: Experimental Setup. (a) Cell Arrangements; (b) Ceiling Installations

Figure 3: Window blinds systems installed in the Reference Cell and Test Cell

Figure 4: Flow diagram for Blinds control used at Skylab

Figure 5: Blind profile for North orientation for working plane illuminance (a) and DGP (b)

Figure 6: Blind profile for West orientation for working plane illuminance (a) and DGP (b)

Figure 7: Lighting energy testing results comparison with T5 fluorescent lamps no dimming from Test 1 reference cell

Figure 8 (a): Zonal lighting power consumption with respect to Sky condition (Test 4 – Test cell, Test 2 – Test cell and Test 2 – Ref cell)

Figure 8 (b): Zonal lighting power consumption with respect to Sky condition (Test 4 – Test cell, Test 2 – Test cell and Test 2 – Ref cell)

Figure 8 (c): Zonal lighting power consumption with respect to Sky condition (Test 6 – Test cell, Test 3 – Test cell and Test 1 – Test cell)

Figure 8 (d): Zonal lighting power consumption with respect to Sky condition (Test 6 – Test cell, Test 3 – Test cell and Test 1 – Test cell)

Figure 9 (a): Zonal lighting power consumption with respect to Sky condition for integrated system with LED lamps in east and north orientation (Test 7 – Test cell, Test 6 – Test cell)

Figure 9 (b): Zonal lighting power consumption with respect to Sky condition for for integrated system with LED lamps in east and north orientation (Test 7 – Test cell, Test 6 – Test cell)

Figure 10 (a): Working Plane Illuminance at inner lighting Zone for first day of Test 1.

Figure 10 (b): Working Plane Illuminance at perimeter lighting Zone for first day of Test 1.

Figure 10 (c) : Working Plane Illuminance at perimeter lighting Zone for first day of Test 3.

Figure 10 (d): Working Plane Illuminance at perimeter lighting Zone for first day of Test 4.

Figure 11 (a): Inner zone working plane illuminance with respect to sky condition for T5 lamps (Test 4 – Test cell, Test 2 – Test cell and Test 2 – Ref cell)

Figure 11 (b): Perimeter zone working plane illuminance with respect to sky condition for T5 lamps (Test 4 – Test cell, Test 2 – Test cell and Test 2 – Ref cell)

Figure 11 (c): Inner zone working plane illuminance with respect to sky condition for LED lamps (Test 6 – Test cell, Test 3 – Test cell and Test 1 – Test cell)

Figure 11 (d): Perimeter zone working plane illuminance with respect to sky condition for LED lamps (Test 6 – Test cell, Test 3 – Test cell and Test 1 – Test cell)

Figure 12: DGP for T5 fluorescent lamps with different lighting and blinds combinations (Test 4 – Ref cell, Test 4 – Test cell, Test 2 – Test cell and Test 2 – Ref cell)

Figure 13 (a) : Inner zones working plane illuminance for Integrated system with LED lamps (Test 7 – Test cell, Test 6 – Test cell)

Figure 13 (b) : Perimeter zones working plane illuminance for Integrated system with LED lamps (Test 7 – Test cell, Test 6 – Test cell)

Figure 14 : DGP for Integrated system with LED lamps (Test 7 – Test cell, Test 6 – Test cell)

Figure 15 : Typical Sky conditions of Singapore using TMY data

Figure 16 : Comparison of annual energy savings through simulation and experimental savings for combined system

ANNEXURE A

- WORKING PLANE ILLUMINANCE CHARTS FOR ALL EXPERIMENTS

Figure 1: Working Plane Illuminance at inner lighting Zone for first day of Test 1.

Figure 2: Working Plane Illuminance at perimeter lighting Zone for first day of Test 1.

Figure 3: Working Plane Illuminance at inner lighting Zone for second day of Test 1.

Figure 4: Working Plane Illuminance at perimeter lighting Zone for second day of Test 1.

Figure 5: Working Plane Illuminance at inner lighting Zone for first day of Test 2.

Figure 6: Working Plane Illuminance at perimeter lighting Zone for first day of Test 2.

Figure 7: Working Plane Illuminance at inner lighting Zone for second day of Test 2.

Figure 8: Working Plane Illuminance at perimeter lighting Zone for second day of Test 2.

Figure 9: Working Plane Illuminance at inner lighting Zone for third day of Test 2.

Figure 10: Working Plane Illuminance at perimeter lighting Zone for third day of Test 2.

Figure 11: Working Plane Illuminance at inner lighting Zone for first day of Test 3.

Figure 12: Working Plane Illuminance at perimeter lighting Zone for first day of Test 3.

Figure 13: Working Plane Illuminance at inner lighting Zone for second day of Test 3.

Figure 14: Working Plane Illuminance at perimeter lighting Zone for second day of Test 3.

Figure 15: Working Plane Illuminance at inner lighting Zone for third day of Test 3.

Figure 16: Working Plane Illuminance at perimeter lighting Zone for third day of Test 3.

Figure 17: Working Plane Illuminance at inner lighting Zone for first day of Test 4.

Figure 18: Working Plane Illuminance at perimeter lighting Zone for first day of Test 4.

Figure 19: Working Plane Illuminance at inner lighting Zone for second day of Test 4.

Figure 20: Working Plane Illuminance at perimeter lighting Zone for second day of Test 4.

Figure 21: Working Plane Illuminance at inner lighting Zone for third day of Test 4.

Figure 22: Working Plane Illuminance at perimeter lighting Zone for third day of Test 4.

Figure 23: Working Plane Illuminance at inner lighting Zone for first day of Test 5.

Figure 24: Working Plane Illuminance at perimeter lighting Zone for first day of Test 5.

Figure 25: Working Plane Illuminance at inner lighting Zone for second day of Test 5.

Figure 26: Working Plane Illuminance at perimeter lighting Zone for second day of Test 5.

Figure 27: Working Plane Illuminance at inner lighting Zone for third day of Test 5.

Figure 28: Working Plane Illuminance at perimeter lighting Zone for third day of Test 5.

Figure 29: Working Plane Illuminance at inner lighting Zone for first day of Test 6.

Figure 30: Working Plane Illuminance at perimeter lighting Zone for first day of Test 6.

Figure 31: Working Plane Illuminance at inner lighting Zone for second day of Test 6.

Figure 32: Working Plane Illuminance at perimeter lighting Zone for second day of Test 6.

Figure 33: Working Plane Illuminance at inner lighting Zone for third day of Test 6.

Figure 34: Working Plane Illuminance at perimeter lighting Zone for third day of Test 6.

Figure 35: Working Plane Illuminance at inner lighting Zone for first day of Test 7.

Figure 36: Working Plane Illuminance at perimeter lighting Zone for first day of Test 7.

Figure 37: Working Plane Illuminance at inner lighting Zone for second day of Test 7.

Figure 38: Working Plane Illuminance at perimeter lighting Zone for second day of Test 7.

Figure 39: Working Plane Illuminance at inner lighting Zone for third day of Test 7.

Figure 40: Working Plane Illuminance at perimeter lighting Zone for third day of Test 7.

Table 1. Summary of test cases

Tests	Reference Cell	Test Cell	Façade Orientation	Daily average Clearness index	Purpose
Test 1	T5 lamps No dimming Blinds: Retracted	LED lamps No dimming Blinds: Retracted	Facing North	11 May 16 : 0.31 01 Aug 16 : 0.35	T5 vs LED at full output
Test 2	T5 lamps No dimming Blinds: Retracted	T5 lamps Auto-dimming on Blinds: Retracted	Facing North	03 May 17 : 0.32 31 Mar 17: 0.26 03 Apr 17 : 0.34	Savings by auto-dimming
Test 3	T5 lamps Auto-dimming on Blinds: Retracted	LED lamps Auto-dimming on Blinds: Retracted	Facing North	02 Aug 16 : 0.52 04 Aug 16 : 0.48 26 May 16 : 0.44	T5 vs LED with auto-dimming
Test 4	T5 lamps Auto-dimming on Blinds: Close	T5 lamps Auto-dimming on Blinds: Automated	Facing North	19 Apr 17 : 0.38 20 Apr 17 : 0.25 21 Apr 17 : 0.39	Savings by automated blinds
Test 5	T5 lamps No dimming Blinds: Close	T5 lamps Auto-dimming on Blinds: Automated	Facing North	05 Apr 17: 0.42 06 Apr 17 : 0.42 07 Apr 17: 0.51	Savings by integrated auto-dimming + automated blinds
Test 6	T5 lamps No dimming Blinds: Close	LED lamps Auto-dimming on Blinds: Automated	Facing North	08 Aug 16 : 0.36 09 Aug 16 : 0.48 10 Aug 16 : 0.45	Base system* vs combined system [#]
Test 7	T5 lamps No dimming Blinds: Close	LED lamps Auto-dimming on Blinds: Automated	Facing East	17 Aug 16 : 0.38 19 Aug 16 : 0.46 23 Aug 16 : 0.41	Base system* vs combined system [#] (façade orientation effect)

* Lighting: T5, Auto-dimming: No, Blinds: manual

Lighting: LED, Auto-dimming: Yes, Blinds: automated

Table 2. Total measured lighting energy consumption and savings

	Lighting Energy Ref. Cell (kWh) (1)	Lighting Energy Test Cell (kWh) (2)	Lighting Energy Savings (kWh) (1) – (2)	Lighting Energy Savings (%) $\frac{(1)-(2)}{(1)} \times 100\%$
Test 1*	10.16	7.75	2.41	23.70%
Test 2	10.47	5.51	4.96	47.37%
Test 3	3.52	2.06	1.46	41.52%
Test 4	9.36	6.54	2.82	30.13%
Test 5	10.70	4.61	6.09	56.92%
Test 6	9.79	2.51	7.28	74.35%
Test 7	9.87	3.66	6.21	62.92%

*Three-day normalised