University Students' Cognitive Performance under Temperature Cycles Induced by Direct Load Control Events

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ABSTRACT

As one of the most common strategies for managing peak electricity demand, direct load control (DLC) of air-conditioners involves cycling the compressors on and off at predetermined intervals. In university lecture theatres, the implementation of DLC induces temperature cycles which might compromise university students' learning performance. In these experiments, university students' learning performance, represented by four cognitive skills of memory, concentration, reasoning and planning, was closely monitored under DLC-induced temperature cycles and control conditions simulated in a climate chamber. In Experiment 1 with a cooling set-point temperature of 22 ºC, subjects' cognitive performance was relatively stable or even slightly promoted by the mild heat intensity and short heat exposure resulting from temperature cycles; in Experiment 2 with a cooling set-point of 24 ºC, subjects' reasoning and planning performance observed a trend of decline at the higher heat intensity and longer heat exposure. Results confirm that simpler cognitive tasks are less susceptible to temperature effects than more complex tasks; the effect of thermal variations on cognitive performance follows an extended-U relationship with performance being relatively stable across a range of temperatures. DLC appears to be feasible in university lecture theatres if DLC algorithms are implemented judiciously.

Keywords: Direct load control; peak demand; cognitive performance; temperature cycles; extended-U relationship; lecture theatres

Practical Implications

Productivity, or human mental performance, is obviously the top priority in educational institutions. A controversial yet popular opinion holds that productivity or human mental performance peaks at a single optimal temperature or thermal sensation, and this supports the call for stringent thermal comfort standards in educational settings. However, the results from this experimental study demonstrate that performance is relatively stable across a broad range of temperatures. These research findings lend support to demand response strategies such as direct load control to reduce peak electricity demands without substantively impacting productivity.

1. Introduction

1.1 Direct load control strategy

Due to their size and high occupant densities, university teaching buildings such as lecture theatres are major contributors to peak electricity loads. Universities often incur peak demand penalties that typically represent up to one fifth of the institution's total electricity costs across a year of operations, even though the peak demand events occur for just a few hours in a year (Zhang and de Dear, 2015). Demand side management strategies such as direct load control (DLC) are among the most common approaches to cope with peak demand. In DLC programs, an electricity utility or aggregator remotely shuts down or cycles on-and-off the consumer's high-demand electrical equipment such as air-conditioning compressors, water heaters, pool pumps, etc. This present study investigates DLC of air-conditioners (AC) that is implemented through duty cycle restrictions (Weller, 2011). Under DLC programs the consumer's AC compressor is switched on and off at predetermined intervals but the system's fan is left running. In the language of DLC the "off cycle fraction" refers to the amount of time the compressor is off during an activation period; "cycling period" refers to the duration of one complete cycle of compressor, on and off (Zhang and de Dear, 2015). Peak load reduction through DLC may not be obvious for a single building or consumer, but when DLC is coordinated across a large number of customers, the utility or aggregator can realise substantial peak load reductions.

In recent years, many utility companies in the western world have witnessed the promising results of DLC AC duty cycle restriction in residential and small business buildings by both reducing peak demands and providing acceptable levels of thermal comfort. However, the application of DLC AC duty cycle restriction in university lecture theatres is rarely seen. Cycling the AC compressors on and off for a given proportion of time will induce the ambient temperature to drift away from the cooling set-point temperature to higher values. Zhang and de Dear (2015) have simulated thermal environmental conditions of a Sydney university lecture theatre during DLC events with variant parameter values and found that the ambient temperatures generally range between 20 ºC to 32 ºC during a DLC event. Before any assessment of DLC feasibility in lecture theatres can be made, one crucial question needs to be answered: will university students' learning performance, which is the top priority over-and-above energy saving, be compromised by DLC events?

1.2 Mental performance under variant thermal environments

Most of the human mental performance studies in the literature have been conducted in steady-state thermal conditions. Generally, these studies fall into two divisions: a first group of interest primarily to military and industrial agencies concerned directly with survival in extreme environments, and a second group concerned with normal individuals in tolerable but adverse thermal circumstances (Hancock et al., 2007).

The effects of *heat stress* on human cognitive performance have been extensively studied. Yet, it is not easy to generalize the impacts in a systematic way. In an excellent review, Hancock and Vasmatzidis (2003) mentioned a diverse pattern of findings: most of the studies reported deteriorated performance during heat (for example, Parsons, 2000; Pilcher et al., 2002; Qian et al., 2015; Muller et al., 2012), but there are also studies which reported no effects of heat stress on mental performance (Dean Chiles, 1958; Bell et al., 1964; Colquhoun, 1969; Nunneley et al., 1979), and some even found performance improvement upon initial exposure to heat (Poulton and Kerslake, 1965; Lovingblood et al., 1967; Colquhoun and Goldman, 1972). Hancock believes that many factors have contributed to the contradictions, such as task complexity, skill levels of subjects, duration of exposure and so on. He also pointed out that heat affects cognitive performance differentially.

Apart from heat stress studies, indoor environmental scientists have also examined the impacts of *moderate* thermal environments on occupants' mental performance, and many investigators have confirmed the *inverted-U relationship* (Griffiths and Boyce, 1971; Kosonen and Tan, 2004; Jensen et al., 2009; Lan et. al., 2011). For example, Kosonen and Tan (2004) report that peak performance occurs when the PMV value is −0.21 at a temperature of 20 °C with a relatively heavy clo value (1.16 clo). Based on the model of Jensen et al. (2009), the optimum performance occurs when the TSV is −1. This is lower than the value predicted from the model by Lan et al. (2011) showing an optimum performance at about TSV value of −0.25. In Seppänen et al. (2006), there are contradictory results being reported for the relationship between thermal environment and performance. Seppänen et al. (2003) first proposed a relation between performance and temperature showing a decrease in performance by 2% per 1 °C increase in temperature in the range of 25 °C–32 °C, *and no effect on performance in the temperature range of 21 °C–25 °C*. However, a subsequent reanalysis of 26 studies reported in Seppänen et al. (2006) clearly presented an inverted-U relationship with performance peaking at 21.6 °C (Fig 1, left). What's more, this ambiguity is further reflected in ASHRAE (2013), which is an official guideline for heating, ventilation and air conditioning (HVAC) engineers. In the text of ASHRAE (2013), it is stated that "a range of temperature at comfort conditions exists within which *there is no significant further effect on performance* (Federspiel, 2001; Federspiel et al., 2002; McCartney and Humphreys, 2002; Witterseh, 2001)." Nevertheless, a figure in ASHRAE (2013) contradicts this statement. In Fig. 1 (right), it is obvious that there is an optimal comfort temperature T_c leading to the 100% relative performance and deviation from this optimal temperature causes a decrement of performance.

Fig. 1 Relative performance vs. temperature derived from Seppänen et al. (2006) (left) and ASHRAE (2013) (right)

There are only a few studies focusing on the mental performance in transient thermal environments. Regarding mental performance during temperature cycles, Wyon et al. (1971) investigated the factors affecting subjective tolerance of temperature swings and found that subjects tolerated greater amplitudes when performing mental work than when resting. Wyon et al. (1973) found that small rapid swings around the preferred temperature decreased performance and work speed. Conversely, larger and slower swings were associated with a higher work speed and accuracy, equal to the performance achieved under steady-state conditions.

As for performance studies under temperature ramps or drifts, there are generally no consistent significant positive or negative results observed by previous laboratory studies (Newsham et al. 2006; Kolarik et. al. 2009; Schellen et al. 2010). Newsham et al. (2006) conducted a controlled laboratory study on the effects of temperature ramps and electric light levels on the subjects' mental performance. Sixty-two participants were divided into two groups. The first group was exposed to a simulated load shed in the afternoon: workstation illuminance level reduced by 2%/min, and temperature increased by up to 1.5 °C over a 2.5 h period; another group experienced no load shed. Analyses revealed that the group experiencing the simulated load shed experienced both positive and negative effects on satisfaction or performance. Kolarik et al. (2009) conducted two related laboratory experiments on operative temperature ramps with different slopes, directions and durations. Subjects' performance was measured by simulated office work and it was concluded that no significantly consistent effects of individual temperature ramps on office work performance were found. Schellen et al. (2010) also examined the effects of moderate temperature ramps on subjects' mental performance. Eight young adults (22–25 years) and eight older subjects (67–73 years) were exposed to a control condition and a moderate temperature ramp.

Performance was assessed using two simulated office tasks: text typing and addition. The results indicated no effect of the temperature change on the performance of the subjects.

1.3 University students' learning performance in lecture theatres

Cognitive learning is a complex process which requires a student to use and apply a range of cognitive skills, including perception and attention, language acquisition and reading, memory, comprehension, problem solving and reasoning, reorganizing and planning. University students' professional skills and abilities can be very different depending on their majors. Rovai et al. (2009) argued that using grades as the sole measure of learning could be problematic, particularly when measuring learning outcomes across disparate courses and content areas. A century of scientific research reveals that the general cognitive ability or *g*, predicts a broad spectrum of important life outcomes including academic achievement (Brand, 1987; Gottfredson, 1997; Jensen, 1998; Lubinski, 2000; Kuncel et al., 2004). In this study, the generic cognitive skills underlying all learning are measured and served as "predictors" of university students' academic learning performances in lecture theatres. Specifically, four main cognitive skills are tested—memory, attention, reasoning and planning.

1.4 Aims and Scopes of the study

Although there are numerous studies on the effects of thermal environment or thermal stress on cognitive performance, few studies were conducted in thermal transient conditions. To date there has been no research published on the impacts of temperature cycles induced by DLC events on occupants' cognitive performance. The present study is an experimental investigation into how DLC-induced temperature fluctuations affect university students' cognitive performance in lecture theatres in terms of four generic cognitive skills of memory, attention, reasoning and planning. This study also examines the relationships between cognitive performance and commonly used thermal comfort indexes, compares these relationships with previous research findings, and comments on the controversy surrounding thermal environmental effects on productivity.

2. Methods

2.1 Climate Chamber

The experiment was carried out in a climate chamber (8.85 m × 6.85 m, 2.60 m in height with an accessible raised floor of 250 mm), in which participants sat at seven workstations, each consisting of a desk, a chair, a personal computer and an IPad. The temperature conditions in the chamber are controlled by a Constant Air Volume system which can adjust air temperature within the occupied zone from 16 ºC to 38 ºC. The outdoor simulation corridor adjacent to the chamber has independent environmental controls which were used to simulate outdoor conditions of typical DLC event days in Sydney. Other technical details about the laboratory can be found in de Dear et al. (2012).

2.2 Panel of Subjects

Fifty-six subjects (28 males and 28 females) were recruited to participate in two separate experiments, 28 subjects (14 males and 14 females) for each. Subjects were recruited from the university students, regardless of age, degree and discipline. They aged 18–47 years (mean age 25 years) and were well-balanced in humanities/engineering disciplines. Participants were required to wear a standard clothing ensemble for the experiments, consisting of a short-sleeve T-shirt, a walk shorts, underwear, and sandals. The ensemble's intrinsic clothing insulation was estimated to be 0.5 clo units including the insulation of the chairs (0.1 clo) used inside the climate chamber, representing typical summer clothing of Australian university students. Participants were paid at a fixed hourly rate. To increase participants' motivation and encourage them to treat cognitive tests seriously, they were told before experiments that a prize would be provided to the highest total cognitive performance score.

2.3 Conditions Tested

There were 8 environmental exposures in two experiments. Participants experienced 1 control condition (no DLC event) and 3 different experimental conditions (DLC temperature cycling conditions) in each experiment. All the 6 DLC (cycling) conditions were designed on the basis of Zhang and de Dears' (2015) simulated indoor thermal environments of a typical university lecture theatre during DLC events with 3 off-cycle fractions (33%, 50% and 67%), 2 cycling periods (0.5 h and 1 h), 2 cooling set-point temperatures (22 °C and 24 °C), 2 building envelope thermal performance levels (good and poor) and 2 ventilation rates (10 L/s/person and 15 L/s/person). Since ventilation rate was found to have the smallest impact on thermal environments during DLC events compared with 4 other parameters (Zhang and de Dear, 2015), the current experiments maintained a constant ventilation rate of 10 L/s/person (deemed typical for Australian university lecture theatres).

The *orthogonal array* is a method of research design that only requires a fraction of the full factorial combinations (Fowlkes and Creveling, 2012) to be tested. In the present study, a mixed level orthogonal array of $\boldsymbol{L_8}$ $(2^4, 4^1)$ was adopted to test a single factor (off-cycle fraction) with 4 levels and 4 other factors (cycling period, cooling set-point temperature, building envelope thermal performance and a blank factor with 2 levels). Apart from the three off-cycle fractions tested in Zhang and de Dear (2015), 0% was a fourth level, serving as the control condition without DLC event. There was a 2-level factor deliberately left blank in order to account for experiment errors. Combinations of all environmental factors in each experimental condition were listed in Table S1. All four conditions in Experiment 1 had a cooling set-point temperature (air temperature) of 22 °C but this was raised to 24 °C for conditions in Experiment 2. The simulated operative temperature (OT) and relative humidity (RH) for each condition were illustrated in Fig. 2 and Fig. 3.

Fig. 2 Simulated operative temperature and relative humidity in four conditions of Experiment 1

Fig. 3 Simulated operative temperature and relative humidity in four conditions of Experiment 2

2.4 Measurements

2.4.1 Physical and comfort measurements

During the experiments, the air temperature (measured at 1.1 m height above floor in the occupied zone), globe temperature, relative humidity and air speed were continuously measured. Illumination within the chamber was fixed at 500 lux, and the background noise during experiments was 40 ± 5 dB. Thermal comfort questionnaires included a 7-point ASHRAE thermal sensation scale and a binary thermal acceptability scale (acceptable—1 / not acceptable—0). These two questionnaires were administered to participants through a bespoke IPad application.

2.4.2 Cognitive performance measurements

Four generic cognitive skills were tested—memory, concentration, reasoning and planning. Two short online cognitive performance tests were selected for each skill. All 8 tests used in this study (Fig. 4) came from the public website of Cambridge Brain Sciences (CBS) Inc.[1] and were based on classical paradigms from the cognitive psychology literature.

Fig. 4 Cognitive performance tests adopted in each cognitive skill in current experiments

For memory skill, the *Digit Span* task tests subjects' verbal working memory by remembering a sequence of numbers that appear on the screen one after the other; the *Spatial Span* task tests subjects' visuospatial working memory by remembering a sequence of flashing boxes that appear on the screen one after the other. For concentration skill, the *Rotations* test is used for measuring subjects' mental rotation abilities which have been found to significantly correlate with route learning (Silverman, 2000), whereas the *Feature Match* test measures subjects' attentional processing by comparing particular features of various shape images to one another and indicating whether the contents are identical. In reasoning skill, the *Odd One Out* task requires participants to work out which of the nine patterns is the odd one out; the *Grammatical Reasoning* task requires participants to indicate whether a statement correctly describes a pair of objects displayed in the centre of the screen. In planning skill, the *Spatial*

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[1] http://www.cambridgebrainsciences.com/

Search is based on a test that is widely used to measure strategy during search behaviour (Collins et al., 1998), and assesses participants' ability to retain and manipulate information in spatial working memory; the *Hampshire tree* task is an adaptation of the *Tower of London/ Tower of Hanoi* test (Shallice, 1982; Simon, 1975), a widely used clinical neuropsychological tool for assessing planning abilities. Detailed descriptions of the 8 cognitive performance tests can be found in the Supplemental Information from Hampshire et al. (2012).

2.5 Experimental Procedure

In each experiment, 28 subjects were divided into 4 sub-groups. Each sub-group has 7 subjects sitting in the climate chamber simultaneously. The sequences at which sub-groups were exposed to different experimental conditions were balanced by *4×4 Latin-square design.* One week before the experiments started, all participants attended a 1h induction session to familiarize them with the experimental procedure, receive training and practise on thermal comfort surveys and online cognitive performance tests. Participants experienced four conditions always at the same time and same day of week throughout four successive weeks. The experimental session lasted for 2.5 hours. During the first half hour, participants acclimatized themselves to the cooling set-point temperatures (22 °C for Experiment 1 and 24 °C for Experiment 2) and practised on the 8 cognitive performance tests. The following 2 hours were formal experiment period in which thermal comfort questionnaires and cognitive performance tests were assigned to subjects. In the majority of 5-min questionnaire intervals, participants were required to do one cognitive performance test on their computers; during other intervals, they were allowed to rest. Schedules of performance tests (see Fig. S1) aimed at a balance between tests and rest. One test in each skill was administered when AC was on and the other test in the same skill administered when AC was off. Water was provided *ad libitum* and light snacks were also provided to ameliorate fatigue and low blood sugar.

2.6 Statistical Analysis

Repeated measurements of the same subjects can be viewed as a hierarchical structure, where multiple observations are nested within individuals. In the current study, experimental data were analysed using Multilevel Linear Models (MLM, also known as hierarchical linear models or mixed linear models) although they can be extended to non-linear models as required. MLM provides an alternative type of analysis for univariate or multivariate analysis of repeated measures, while retaining all the available data and within-subject variance. Only fixed effects were the research interest of this study. *Sequence effect*, a common confounder for within-subject designs, could also be tested and adjusted by setting up the "sequence" as an independent variable in MLM apart from other determinants. This is similar to conduct an "analysis of covariance" where dependent variable scores are adjusted for covariates prior to testing treatment differences. Predictors which did not have a meaningful zero point (such as air temperature) were centred by their grand mean in each experiment. MLM was implemented through SPSS Mixed Models, Version 22.

3. Results

The recorded range of air temperature and the mean RH in the occupied zone for each exposure condition during two experiments were reported in Table 1, along with the antique thermal comfort index, Effective Temperature (ET, Houghton and Yagloglou, 1923a; 1923b), to express combined temperature-humidity comfort for comparisons with some older literature in the domain of temperature effects on performance. Due to limited precision on HVAC control, the temperature range actually achieved for the control conditions was approximately 2 °C. Subjects' mean thermal sensation vote (TSV), mean thermal acceptability vote, as well as calculated mean predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) indexes for comparison were also reported in Table 1 with their respective standard deviations. TSV was generally lower than predicted by PMV and incurred larger variations; the mean thermal acceptability was consistently higher than the predicted percentage satisfied inferred from PPD. Since all conditions in Experiment 1 started from the cooling set-point temperature of 22 °C while 24 °C in Experiment 2, the air temperature and TSV in Experiment 2 were generally higher.

Table 1 The recorded range of air temperature and ET, Mean RH, TSV, PMV and PPD with standard deviation (SD), mean thermal acceptability for each condition

The mean and standard deviation of 8 cognitive performance tests in both experiments were listed in Table S2 and compared with corresponding general benchmark results reported in Hampshire et al. (2012) based on all users of the CBS website. The scoring of each of the eight cognitive performance tests was very different. Also, cognitive performance differences between subjects could be larger than the intrapersonal differences caused by thermal environments. Therefore in order to compare test scores between different participants and cognitive test types, each participant's score was normalised using the average score of the same person on a particular cognitive test under the control condition (Condition 1 for Experiment 1 and Condition 8 for Experiment 2). To be specific, the mean of the two test scores for a participant in the control condition was set to 100; other scores of the same participant under DLC temperature cycling conditions were then converted *pro-rata* according to the reference score.

3.1 Tests of sequence effects

In a within-subject research design there are two basic types of sequence effects—practice (learning) and fatigue. Participants potentially develop a better skill in the cognitive performance tests throughout the four experimental weeks, which is referred to as a learning effect. This has been partially controlled by the *balanced 4×4 Latin-square design* in this experiment, but not completely, since the learning effect of each sub-group may vary between different experimental conditions, as reported by Cui et al. (2013a and 2013b). Furthermore, there may be fatigue effects superimposed upon learning effects because each participant took 2 sets of the 8 cognitive performance tests within each two-hour formal experiment period.

This complicated double sequence effect could not be controlled by a *balanced 4×4 Latin-square design*.

Possible sequence effects in repeated cognitive performance tests, both along the experimental weeks and within an experimental session, were tested in MLM. Effects of sequences along experimental weeks have been tested up to the quadratic forms. Considering there were only four measurements along the weeks, a linear trend was generally adequate to represent the learning process, with the exceptions being the *Hampshire Tree* test and the overall cognitive performance in both experiments, where significant quadratic learning trends were detected. An index of overall cognitive performance was obtained by pooling the 8 performance test results into one dataset. The regression coefficients for two sequence effects in both experiments have been listed in Tables S3 and S4. Positive regression coefficients suggest learning effects were predominant, while negative coefficients imply fatigue dominated. In both experiments, the majority of the 8 cognitive performance tests demonstrated significant learning effects through experimental weeks, while one or two tests showed evidence of a significant learning effect within experimental sessions. These results indicate that in within-subject performance measurement experiments, significant learning effects often occur; therefore results need to be adjusted for them before treatment effects can be thoroughly explored.

3.2 Effects of experimental conditions on cognitive performance

3.2.1 Within-subject comparisons

After adjustment for significant sequence effects, the effect of experimental conditions on participants' 8 performance tests as well as the overall cognitive performance index was examined for both experiments in multilevel models. The results are summarized in Table 2. The marginal means of cognitive performance test scores with 95% Confidence Interval (CI) were calculated for 8 cognitive performance tests in both experiments, after adjustment for significant sequence effects (illustrated in Fig. 5 and Fig. 6). Generally the overall effect of experimental conditions did not have a significant impact on cognitive performance tests. However, there are three exceptions to this generalisation: the *Digit Span* test, the *Rotations* test in Experiment 1(p < 0.05 for both) and the *Hampshire Tree* test in Experiment 2 (p < 0.01). *Post hoc* procedures (*Sidak* adjustment for multiple comparisons) were then applied to further detect significant pairwise comparisons. For the *Digit Span* test in Experiment 1, performance scores in Condition 2 were significantly higher than they were in Condition 1 (p < 0.05). Regarding the *Rotations* test in Experiment 1, there was significant difference (p < 0.05) in test scores between Conditions 1 and 4. In the *Hampshire Tree* test in Experiment 2, there were two significantly different pairwise comparisons—Conditions 5 and 8 (p < 0.01) and Conditions 6 and 8 (p < 0.05). The pooled dataset suggested that overall cognitive performance in Experiment 1 has significant differences between conditions while there were none in Experiment 2. Fig. S2 plots estimated marginal means for subjects' overall cognitive performance in the two experiments. *Post hoc* procedures revealed that performance was significantly higher in Condition 4 than in Condition 1 (p < 0.05) in Experiment 1. In the above-mentioned three significant performance tests as well as the pooled overall cognitive performance in Experiment 1, there was a consistent performance *enhancement* during DLC temperature cycling conditions compared to static control conditions (although not all pairwise comparisons reached statistical significance).

Table 2 Effects of different experimental conditions on cognitive performance tests in two experiments

Fig. 5 Estimated marginal means of 8 cognitive performance tests with 95% CI in Experiment 1 after adjustment for significant sequence effects

Fig. 6 Estimated marginal means of 8 cognitive performance tests with 95% CI in Experiment 2 after adjustment for significant sequence effects

3.2.2 Between-subject comparisons

The experimental design of this study does not permit valid comparison of cognitive performance between the two control conditions—Condition 1 at a steady 22 °C and Condition 8 at a steady 24 °C—for the reason that subjects' interindividual differences in cognitive performance are quite likely to be larger than the intraindividual differences resulting from the two environmental exposures. However, normalising of test scores still permits between-subject comparisons between different DLC temperature cycling conditions (Conditions 2 through 7) in the two experiments. Each DLC(cycling) condition in Experiment 1—Conditions 2, 3 and 4 was compared with the three Experiment-2 conditions (5, 6 and 7) simultaneously by setting up dummy variables with the Experiment-1 group as the reference. All the significant between-subject comparisons of cognitive performance tests have been identified and detailed in Table 3. The two sequence effects—learning and fatigue—were also tested.

Table 3 Between-subject comparisons of different DLC temperature cycling conditions (only significant comparisons were included)

For the majority of cognitive tests, performance scores under the various DLC temperature cycling conditions of Experiment 1 (from cooling setpoint of 22 °C) did not significantly vary from their counterparts in Experiment 2 (cycling from cooling setpoint of 24 °C). However, it was interesting to note that in Table 3, performance tests with significant between-subject comparisons were all memory tests and, without exception, memory test scores in Experiment-2 groups were lower than those in the corresponding Experiment-1 reference group. The estimated marginal means with 95% confidence interval for 6 DLC temperature cycling conditions in the Digit Span and the Spatial Span tests were then plotted from the multilevel models (see Fig. S3). Although not all pairwise comparisons reached significance, there was a general trend that subjects' memory performance scores in Experiment 1 were higher than their counterparts in Experiment 2, suggesting that DLC events (temperature cycles) starting from lower temperatures might be associated with relatively higher memory performance of occupants. Also, comparing the six DLC conditions, Condition 3, 4 and 7 are large and slow temperature cycles with longer cycling periods (1 h) and larger fluctuation amplitudes (5–7 °C air temperature) whereas Condition 2, 5 and 6 are small and rapid temperature cycles with shorter cycling periods (0.5 h) and smaller fluctuation amplitudes (3–4 °C air temperature). As opposed to the results by Wyon et al. (1973) where 7 temperature cycles were examined—2 and 4 °C /8 min, 2, 6 and 8 °C /16 min, 4 and 8 °C /32 min, results from the present study do not show any significant difference in cognitive performance between large temperature cycles (Condition 3, 4 and 7) and small temperature cycles (Condition 2, 5 and 6).

3.3 Effects of different cycling stages on participants' four cognitive skills

As discussed in Section 2.5, two groups of cognitive performance tests representing four generic cognitive skills were assigned to participants at different points in the DLC-related heating, ventilating and air-conditioning (HVAC) cycling, namely "cycling on" stage and "cycling off" stage. Because of this experimental design it was possible to compare the same subject's four cognitive skills between different cycling stages. Table 4 listed cognitive skills observed to significantly differentiate between cycling on and cycling off stages under the 6 temperature cycling conditions. In Condition 2, participants' reasoning performance was higher during "off cycle" stage than during "on cycling" stage; so was the memory performance in Condition 3. Yet, these two effects were relatively isolated instances. In all three cycling conditions of Experiment 2 (24 °C cooling setpoint), subjects' planning performance was significantly higher during "cycling on" stage than "cycling off" stage, indicating that in warmer DLC conditions (temperature cycles starting from higher temperatures), HVAC cycling stage might have an impact on subjects' planning performance, specifically, "cycling on" stage is associated with higher planning performance.

Table 4 Cognitive skills with significant score differences observed between different stages of DLC-induced temperature cycles

3.4 Relationship between cognitive performance and thermal environment

Subjects' cognitive performance was tested against commonly used thermal comfort indexes, including instrumental observations of operative temperature and subjective TSV, and these relationships were compared with previously published research findings. The correlation between cognitive performance and the rate of temperature change as well as cognitive performance and thermal acceptability were also tested. According to previous literature (Hensel, 1981; Hensen, 1990), the rate of temperature change is related to occupants' thermal sensation during thermal transient conditions, thus seems reasonable to expect it to also have an influence on cognitive performance during DLC-induced temperature cycling events. The rate of temperature change was calculated by the operative temperature change in five minutes, expressed by either a positive or negative value for warm or cold trends in °C/h respectively. Multilevel models were adapted to these purposes after adjusting performance metrics for the two possible sequence effects. First, the tests were performed separately for each of the cognitive skills; then all the data were pooled together to represent the overall cognitive performance of participants.

3.4.1 Relationship between four cognitive skills and thermal comfort indexes

For each experiment, subjects' cognitive performance scores in four cognitive skills were separately tested against TSV, centred air temperature (c-Ta), rate of temperature change and thermal acceptability. Based on previous literature, both TSV and centred air temperature have been tested up to their cubic forms in a sequence of lower-order to higher-order. If the lower order term was significant it was retained when testing the higher orders, otherwise the insignificant lower order term was removed from the model. The regression coefficients for these tests were listed in Table 5 and Table 6 for Experiments 1 and 2 respectively.

Table 5 Dependence of test scores in four cognitive skills on TSV, centred air temperature, rate of temperature change and thermal acceptability —Experiment 1 with cooling setpoint of 22 °C

Table 6 Dependence of test scores in four cognitive skills on TSV, centred air temperature, rate of temperature change and thermal acceptability—Experiment 2 with cooling setpoint of 24 °C

In the cooler of the two experiments—Experiment 1 (Table 5), two significant relationships were discovered ($p < 0.05$)—planning performance was dependent on the cubic of thermal sensation (TSV^3), and concentration performance was related to the rate of temperature change. The positive regression coefficients for both relationships indicated that planning performance increased when TSV was ascending, and that concentration performance was elevated when the temperature rose faster. The relationship between memory performance and centred air temperature was very nearly significant at p =0.066 and the positive coefficient indicated that memory performance was slightly boosted when the air temperature was higher than the grand mean in Experiment 1—24.4 °C.

In the warmer experiment—Experiment 2 (Table 6), there were no significant relationships detected for memory skill. As in the cooler experiment reported in the preceding paragraph, concentration performance had a nearly significant, positive linear relationship with centred air temperature (p =0.070), implying better concentration performance when the air temperature was higher than the grand mean in Experiment 2—25.7 °C. For reasoning skill, subjects' performance score was negatively correlated with TSV^2 ($p < 0.05$), which predicted an optimal reasoning performance around a neutral thermal sensation. Reasoning performance also had a significant relationship ($p < 0.05$) with $c\text{-}Ta^3$ (coefficient -0.07); scatterplots showed that reasoning performance was relatively stable through the air temperature range of 23–28 °C and started to decline around 29 °C. Reasoning test scores for those voting the thermal environment as "acceptable" were 4.67% higher than those who have voted "not acceptable" ($p = 0.078$). Planning skill in Experiment 2 observed the most significant effects. There was a highly significant negative linear relationship between performance scores and TSV ($p < 0.001$), indicating that planning performance significantly went down when TSV increased. Also, planning performance was significantly related to centred air temperature in both first ($p < 0.001$) and second orders ($p < 0.05$). However, this relationship showed an interesting trend: planning performance first decreased with heat, and then went up at higher temperatures. Separate scatterplots of the *Spatial Search* test and the *Hampshire Tree* test results demonstrated distinct patterns. The *Hampshire Tree* test revealed an obvious inverted-U relationship with air temperature, while the *Spatial Search* test scores were more stable and only slightly increased at both ends. Planning test scores for those who have voted the thermal environment "acceptable" were 11.52% higher than those who have voted "not acceptable" ($p < 0.01$), suggesting that an acceptable thermal environment was associated with better planning performance. The negative coefficient -0.54 for the rate of temperature change was highly significant ($p < 0.001$), representing that faster temperature increment significantly correlated with further decrement of planning performance.

3.4.2 Relationship between overall cognitive performance and thermal comfort indexes

In previously published literature on thermal effects on performance (Seppänen et al., 2006; Lan and Lian, 2009; Lan et al., 2011), researchers pooled all the test scores from different performance tests together to represent the overall performance or productivity that was then subjected to analyses with environmental air temperature observations or (and) subjective assessments of warmth, TSV. To facilitate comparison with these earlier studies, the data for the four cognitive skills were pooled for each experiment. Resultant overall cognitive performance index scores was also analysed by MLM after adjusting for sequence effects. In Experiment 2, the interaction effect between two sequences was statistically significant, suggesting a positive moderation effect of one sequence on the other. Regression coefficients and corresponding significance levels were shown in Table 7.

Table 7 Quantitative relationship of overall cognitive performance index with TSV, centred air temperature, rate of temperature change and thermal acceptability in two experiments

In Experiment 1, the only significant relationship was between overall cognitive performance and rate of temperature change ($p < 0.05$). The positive coefficient revealed that overall cognitive performance in Experiment 1 was enhanced when the temperature changed faster towards the warm direction. There are two significant effects in Experiment 2—the relationship between overall cognitive performance and TSV^2 ($p < 0.05$) as well as overall cognitive performance and thermal acceptability ($p < 0.01$). Subjects' overall performance achieved the maximum around a neutral thermal sensation, and performance scores in an acceptable thermal environment were 5.03% higher than in an unacceptable environment.

4. Discussion

4.1 Influencing Factors in the experiment

Hancock and Vasmatzidis (2003) identified a range of factors affecting building occupants' performance in the heat: task complexity, skill levels of subjects, duration of exposure, acclimatization level of participants, incentives, subjects' knowledge of performance results, to mention just a few. Different combinations of these and different ranges of their values no doubt explain complex and often conflicting findings prevalent in the literature on this topic. In the current study, the duration of exposure to different heat intensities is contingent upon the characteristics of the DLC algorithm in each experimental exposure. The longer the off cycle fraction and cycling period, the higher the initial cooling set-point temperature, the poorer the building envelope thermal performance, the higher the heat intensity and the longer exposure to heat will be. Generally speaking, subjects in Experiment 2 were exposed to higher average temperatures for longer durations than their counterparts in Experiment 1. Comparison of performance results between Experiment 1 and 2 helped to understand the joint effects of heat intensity and the duration of exposure.

Since the main focus of this study was the effect of various heat intensities and durations of exposure induced by DLC temperature cycles on four cognitive skills with distinct task complexity, other potentially confounding factors were controlled as much as possible in the experimental design. For example, the same acclimatization time and providing immediate performance results to the participants helped to eliminate two potential confounders.

The skill levels of subjects, obviously, cannot be completely synchronized to the same level for every subject. The current experimental design only guaranteed adequate and the same duration of training for all subjects before experiments began. Nevertheless, significant learning effects were still observed in many performance tests, as was the case in some previous publications (Lan et al., 2011; Cui et al., 2013a and 2013b). Clearly pre-experimental training does not necessarily eradicate learning effects in experimental research designs and learning effects need to be taken into account when testing for treatment effects.

Another confounding factor is incentive or bonus. Previous studies have shown that high incentives increase subjects' motivation which may override mild deleterious effects of environmental exposure (Pepler, 1958; Lan et al., 2010; Cui et al., 2013b). Cui et al. (2013b) also found that motivation was a better predictor of human performance than environmental temperature. In this study, in order to examine the pure temperature or integrated thermal effects on cognitive performance, a small incentive was provided to the subjects. This modest incentive served as a constant motivation throughout the experiments but was not overly generous to the point swamping any thermal environmental impacts.

4.2 Two general trends

The tests of cognitive skills and thermal comfort indexes in the present study have revealed diverse pattern of findings. Nonetheless, these results were generally in support of two claims that some previous studies have made.

First, temperature (or heat) affects cognitive performance differently, depending on the complexity of the tasks. Simple tasks which require less attentional and mental efforts are less vulnerable to heat than more attention-demanding and complex tasks (Hancock and Vasmatzidis, 2003). This trend is most conspicuous in Table 5 and Table 6—memory and concentration skills are relatively stable or even improved in both experiments under the DLC-induced temperature cycles, but reasoning and planning skills, which require a combination of different cognitive skills including short-term memory and concentration, are more vulnerable when the intensity of heat and exposure duration increased in Experiment 2. Among the four skills tested, planning or forward-thinking is the most demanding and complex. Subjects must first mentally create representations of where they are now (current stage) and where they aim to be (goal stage), and then figure out how to transform the current stage to the goal stage while searching and assessing the effectiveness of possible solutions. In the current experiment, analysis revealed that planning skill is the most sensitive to heat in that not only rising temperature itself, but also rate of temperature increment has detrimental effects on planning performance. Reasoning skill also demonstrates the trend of performance decrements in the warmer conditions of Experiment 2.

Second, the effects of environmental temperature or thermal stress on cognitive performance follow an extended-U relationship (Hancock and Warm, 1989; Hancock and Ganey, 2003) — cognitive performance is relatively stable across a broad central plateau region of moderate thermal environments, bound by regions of progressive performance efficiency decrements in more extreme environmental conditions towards the margins beyond the comfort zone (Fig. 7). This model assumes that adverse effects of heat are exerted on occupants by consuming and eventually draining their attentional resources. Within the comfort zone, little compensatory action is needed from occupants to maintain a near-optimal performance. When the stress goes beyond the comfort zone, attentional resources are gradually drained. At first, similar or even enhanced levels of performance can still be maintained via psychological adaptive behaviours such as attentional focus. But when stress levels (duration, or intensity, or both) continue to rise, performance finally breaks down after the depletion of attentional resources. This model easily lends itself to the current findings in Table 5–Table 7. In

Experiment 1 with lower heat intensities and shorter durations of heat exposure, all four cognitive skills plus the pooled overall cognitive performance index show either no change of performance or even performance increment over a large range of temperatures (air temperature range 21.3–31.2 °C, ET range 19.7–28.6 °C). In Experiment 2 with higher heat intensities and longer heat exposure durations, more complex cognitive skills such as reasoning and planning, along with the combined cognitive performance index all demonstrate declining trends when subjects' thermal sensation assessments were on the increase, even though the range of temperatures in Experiment 2 is only moderately elevated (air temperature ranged from 23.0 to 31.5 °C, ET range 21.1 to 28.9 °C).

Fig. 7 The extended-U model between stress and performance (Hancock and Warm, 1989; Hancock and Ganey, 2003)

To sum up, findings from this study do not support the prevalent postulation of inverted-U relationship featuring a single optimal temperature or TSV for cognitive performance. As stated in de Dear et al. (2013 and 2014), the weight of evidence does not favour this "single optimum temperature or TSV hypothesis", and the findings in the current experimental study have provided further evidence for this claim. The inverted-U relationship has been prevalent in the productivity literature and the ASHRAE Handbook of Fundamentals for many years. As such, they have exerted a pervasive influence over building management practices worldwide. Countless previous studies have stressed that the value of labour in an office building is orders of magnitude higher than the HVAC operational energy costs (eg. Woods, 1989; Seppänen, 1999; Roelofsen, 2002; Lan and Lian, 2009), and this logic has been used to justify very stringent thermal comfort standards and temperature control. The logic has even propagated into the lease contracts for premium-grade office space. However, results from this study clearly demonstrate that optimal (or very near-optimal) cognitive performance can still be maintained even in warm temperatures resulting from demand response strategies such as DLC, on the proviso that DLC algorithms are judiciously customized to the specific building (Zhang and de Dear, 2015).

An area that merits a thorough examination in the future is the complex links between moderate thermal discomfort, concomitant thermo-physiological responses, and cognitive performance decrements. Several researchers have proposed the Effective Temperature (Houghton and Yagloglou, 1923a; 1923b) of 29.4 °C as the threshold of "prescriptive zone" (Lind, 1963) and "zone of thermal tolerance" (Hancock and Vercruyssen, 1988), which serves as the upper limit for stasis in deep body temperature. Hancock and Vasmatzidis (2003) claim that above this threshold, human body begins the process of heat storage, and the corresponding increase of core body temperature is inevitable, followed by cognitive performance breakdown. However, in the current experiments performance decrements in reasoning and planning skills were detected in thermal regimes well below this threshold. Unfortunately, the absence of deep body temperature measurement in the present study precludes correlations between thermo-physiological state and cognitive performance. Interestingly enough, Hancock et al. (2007) also report greater cognitive performance decrement below the 29.4 °C Effective Temperature threshold, so this area of confusion requires clarification in future research.

5. Conclusions

This experimental study has explored university students' learning performance, represented by memory, concentration, reasoning and planning cognitive skills during temperature cycles induced by various DLC events. The following conclusions can be drawn:

- Adequate pre-experiment training does not necessarily remove all the learning effects during experimental process. Examination and proper adjustment of learning effects are needed before tests of treatment effects can be validly performed.

- Generally the DLC-induced temperature cycles in either the cooler or warmer experiment do not significantly affect participants' scores on 8 cognitive performance tests, with a few exceptions, confirmed by both within-subject and between-subject comparison. Tests of HVAC cycling stages on four cognitive skills suggest a consistently higher planning performance during "AC on cycle" compared with the "AC off cycle" in Experiment 2.
- Tests of cognitive performance against thermal comfort indexes have bifurcation between the findings of these two experiments. In Experiment 1 with lower heat intensity and shorter heat exposure, performance is generally stable with two cognitive skills even being enhanced in the moderate heat; in Experiment 2 with higher heat intensity and longer heat exposure, reasoning and planning performance shows a decline with elevated environmental temperature or subjective warmth (TSV), or both.
- Results from this study have confirmed two important findings from previous studies: simpler cognitive tasks are less vulnerable to heat than more complex ones; the effect of moderate thermal environments on cognitive performance follows an extended-U relationship, where performance remains relatively stable over much of the central, tolerable temperature range.
- DLC-induced temperature cycles are not likely to exert significant negative impacts on university students' learning performance on the proviso that DLC algorithms are judiciously designed. The DLC strategy is feasible in university lecture theatres.

Supporting Information

Supporting information includes four tables and three figures and can be found with this article online.

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