THERMAL COMFORT AND COGNITIVE PERFORMANCE UNDER PEAK DEMAND AIR-CONDITIONING MANAGEMENT STRATEGIES

FAN ZHANG

A Thesis submitted in fulfilment of the requirements for the degree of
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THE UNIVERSITY OF SYDNEY

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Abstract

The increased frequency of heatwave occurrences expected in Australia as a result of global warming gives rise to peak demand problems on the electricity grid, mostly driven by the excessive use of air-conditioning. For large institutional electricity consumers like universities, meeting their peak demand is usually at the cost of very significant penalty tariffs from their electricity utility company. Direct load control (DLC) of air-conditioning is increasingly being adopted in Australian universities as a strategy aimed at curtailing peak load, but the thermal comfort and cognitive performance impacts of DLC strategies have, to date, not been researched.

This research focuses on university students' thermal comfort and cognitive performance in thermal conditions induced by the duty cycle restriction approach in DLC events during summer heat-waves. Research methods include both computer simulation and laboratory studies with human subjects. The specific indoor thermal environments resulting from three off cycle fractions, two cycling periods, two cooling setpoint temperatures, two different building envelope thermal performance conditions, and two ventilation rates, were simulated within an EnergyPlus model of a university lecture theatre located in sub-tropical Sydney. With the help of the orthogonal array method, eight representative parameter combinations were selected from 48 EnergyPlus simulations for closer examination using human subjects in climate chamber experiments. Fifty-six subjects in two separate experiments were exposed to three DLC conditions and one control condition inside a simulated "lecture theatre". During the experimental exposure periods, subjects completed "right-here-right-now" thermal comfort surveys and online cognitive performance tests.

The EnergyPlus lecture theatre simulations indicated that the overwhelming majority of the 48 DLC scenarios produced indoor environmental conditions exceeding the permissible comfort range, as defined by the Predicted Mean Vote (PMV) and

Predicted Percentage Dissatisfied (PPD) methods within ASHRAE Standard 55-2013. However the climate chamber experiments found that all the eight conditions yielded an average thermal acceptability of higher than the normative 80% limit. The human subjects' thermal comfort zone during DLC events was wider than predicted by ASHRAE's PMV/PPD model. Also, these human subject experiments suggest that ASHRAE 55-2013 is overly conservative in defining the limits for temperature cycles, ramps and drifts.

Analysis of participants' cognitive performance tests confirmed that simpler cognitive tasks are less susceptible to temperature effects than more complex ones. Furthermore, in contrast with the prevailing belief in the research literature about a single optimum temperature or thermal sensation for maximum performance, the present results indicated that the effects of thermal variations followed an extended-U relationship, with cognitive performance being stable across a relatively broad range of indoor temperatures.

Results from this study reveal that as long as the DLC algorithms are judiciously designed and tailored to the specific building physics and occupancy conditions, DLC events can be readily accepted by university students without incurring thermal discomfort or performance decrements. The current research findings lend support to demand response strategies such as direct load control to reduce peak electricity demands in university buildings.

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1. INTRODUCTION

This chapter discusses the environmental and social background of the research topic; the aim and scope of the study are also defined.

1.1. Heatwaves and Global Warming

Defined by the Australian Bureau of Meteorology (ABOM), heatwave describes three days or more of high maximum and minimum temperatures that are unusual for that location (ABOM, accessed 12-01-2016). Studies report that due to climate change, heatwaves in Australia will be of greater severity, longer duration and higher frequency (Climate Council of Australia, 2014; Hennessy, 2014). The year 2013 was Australia's warmest year since records began in 1910 (ABOM, 2014). During this year, numerous heat records were set, including Australia's longest continent-wide heatwave on record. Following 2013, 2014 was Australia's third-warmest year (the second-warmest being 2009) (ABOM, 2015). From late 2013 to early 2014, much of the central and eastern interior of Australia was plagued by a heatwave. Although it was not as extensive and prolonged as the heatwave in January 2013, substantial areas had their hottest day on record. The year 2015 was another warm year. There were a number of significant heatwaves and warm spells across Australia, such as a rare autumn heatwave across northern and central Australia during March, an early-season heatwave in October affecting nearly all southern Australia, and extreme December heat across much of southeast Australia (ABOM, 2016).

Clearly, Australia is warming up. Eight of Australia's ten warmest years on record have occurred between 2002 and 2015 (ABOM, 2016). The past three years have all been in the top five (ranking first, third and fifth). The 10-year mean temperature for 2006–2015 was the second highest on record at 0.53 °C above average (and just behind 2005–2014) (ABOM, 2016). The year 2011 was the only year in the past ten that was cooler than average.

A warming climate is not a uniquely Australian phenomenon—it is happening globally. ABOM (2016) points out that no year since 1985 has recorded a below-average global mean temperature and all of the ten warmest years have occurred between 1998 and 2015. Scientists at the UK Met Office have claimed that the year 2015 was the warmest year in a record dating back to 1850. The calculated global average temperature of 2015 was 0.75 ± 0.1 °C above the long-term (1961–1990) average (Figure 1-1), and around 1 °C above the long-term average from 1850–1900 (UK Met Office, 2016).

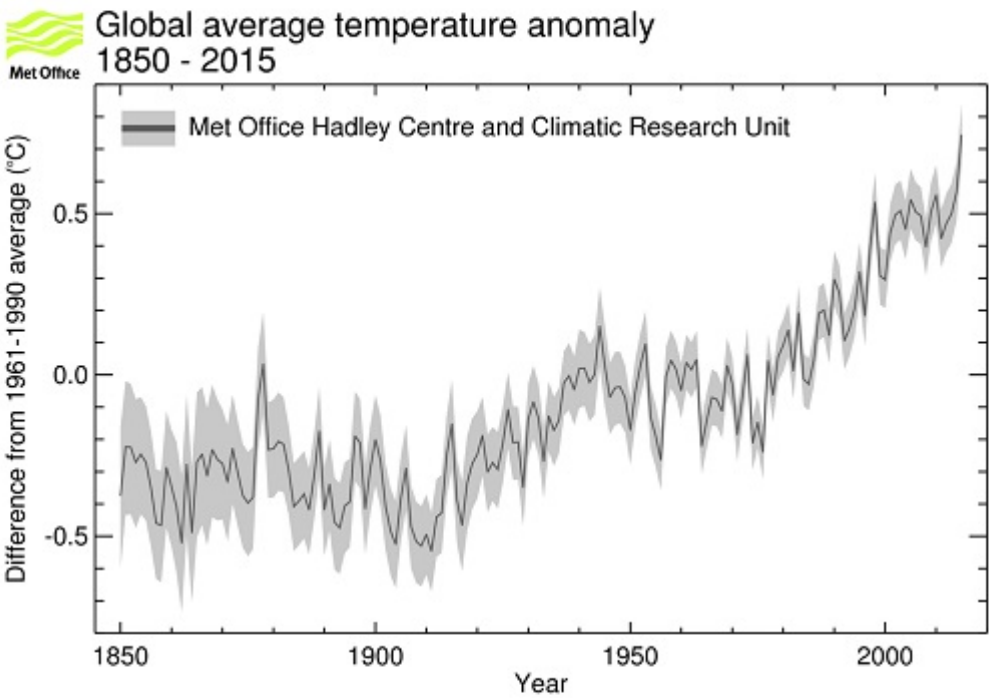


Figure 1-1 Observed global average temperature difference from the 1961−1990 average (°C) (UK Met Office, 2016).

The extreme heatwaves around the world—such as the European heatwave of 2003, the Russian heatwave of 2010, and US heatwaves during 2011 and 2012, were highly unusual with temperatures typically three standard deviations (3σ) warmer than the local climatological norm. This hot extreme that affected much less than 1% of Earth's surface during the base period (1951–1980), now typically covers about 10% of the land area. (Hansen et al., 2012).

To make things worse, carbon dioxide, which is deemed the main driver for global warming, will inevitably trigger more severe and frequent heat waves regardless of emissions between now and 2040, based on the climate modelling results from Dim & Alexander (2013). But targets adopted today for curbing greenhouse gas emissions will determine whether the pattern stabilizes thereafter, or grows even worse.

It is crystal-clear that urgent measures to cut greenhouse gas emissions are needed. During the recently-ended 2015 United Nations Climate Change Conference held in Paris, 195 nations agreed a historic deal to fight global warming by keeping the world's temperature rise under 2 °C, with an ambition to restrict the rise to a long-term goal of 1.5 °C even though 2015 saw us reach the half-way mark. Hopefully, all the participating nations will fulfil their promises, averting the catastrophic global warming beyond 2 °C of warming.

1.2. Peak Demand and Demand Side Management

Unlike many weather hazards that wreak havoc across entire landscapes, such as flood, bushfire and hurricane, impacts of heatwaves seem to command less media attention. But, there is no denial that heatwaves inflict detrimental impacts on public health, infrastructure, natural ecosystems and agriculture (Climate Council of Australia, 2014).

> The heat was so oppressive that the massive increase in people using air-conditioners caused a breakdown in Melbourne's electricity grid - leaving half a million homes without power. (Macdowall & Malkin, 2009)

> According to Los Angeles Department of Water and Power, over 29,000 people in Los Angeles don't have electricity today. There was a massive power blackout according to the agency due to a tremendous power demand yesterday wherein several transformers have exploded. (EJCNN, 2010)

These large-scale power blackouts during both Melbourne heatwave of 2009 and Los Angeles heatwave of 2010 did not happen just by chance. People naturally demand significantly more power to keep comfortable whenever outside temperatures are particularly hot or cold. That's why heatwaves, cold snaps and other similar events can create major spikes in electricity usage, known as *"peak" demand*.

Network capacity is determined by the technical design limits of individual network elements, thus cannot be increased suddenly to meet the peak demand. As network usage approaches or exceeds capacity limits, there may be damage to equipment and loss of network performance, which could even lead to a partial or full system shutdown (AEMC, 2008). In order to prevent supply failures, networks have to be built to exceed the peak demand, meaning that they must be able to accommodate the "peakiest" events in any instant (Figure 1-2).

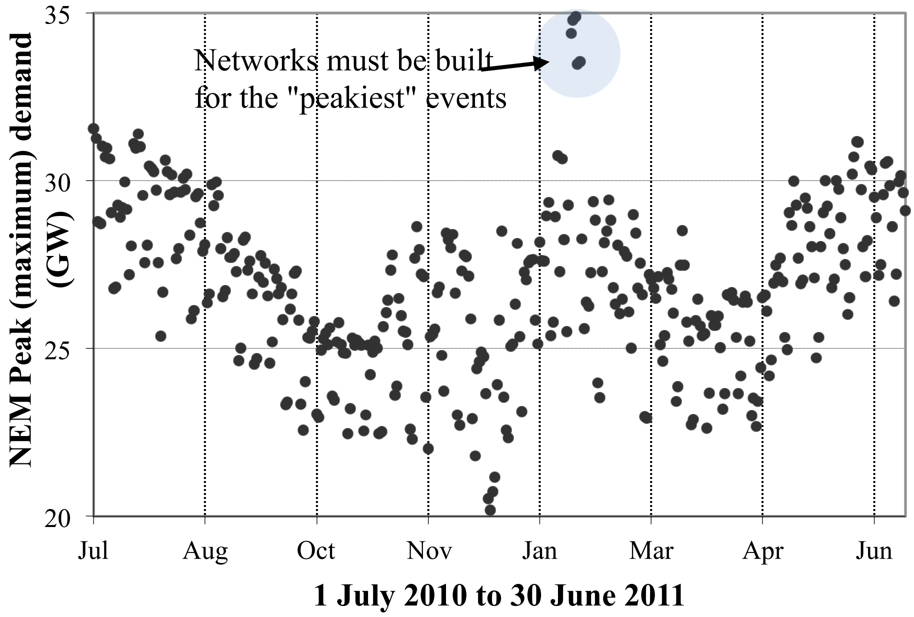


Figure 1-2 Networks must be built for the "peakiest" events (Productivity Commission, 2013)

The "peakiest" events do not often occur; on the contrary, they rarely happen. However, these rare and short-lived high electricity demands call for a large share of generation and network investment, boosting the electricity tariff for everyone regardless of whether they contribute to the peak demand or not. According to AER (2012), around 20%−30% of the $60 billion of electricity network capacity in the national electricity market (NEM) is barely used for 90 hours a year. Capital investments in combatting "peak load growth" are taking up about 45% of total expenditures in the distribution network and more than half of them in the transmission network (AEMC, 2012).

The increasing peak demand in the NEM is driven primarily by growth in *air-conditioning (AC)*, especially in residential and small commercial buildings, and the rate of growth has accelerated sharply in the past few years. It is estimated that typically about 30–40% of commercial sector demand and 40%–50% of residential sector demand on summer maximum demand days is now due to air-conditioning (Matosin, 2012).

Due to the significant future potential value in reducing growth-related infrastructure and constraining rises in electricity tariffs, initiatives to curtail or shift peak load rather than meeting it have gained momentum in many developed countries in recent decades. *Demand side management* or *demand response* (DR) is such a strategy that provides incentives for consumers and businesses to reduce consumption at peak times and, where possible, shift the timing of their power use to non-peak times (Productivity Commission, 2013). DR can be divided into two basic categories: the *incentive-based programs (IBP)* and the *price-based programs (PBP)*. IBP refers to programs where consumers receive load reduction incentives that are separate from, or additional to, their retail electricity tariff, whereas PBP refers to changes in usage by consumers in response to changes in the tariffs they pay (US Department of Energy, 2006). Figure 1-3 shows the sub-classification of DR.

Direct load control (DLC) programs, which are the focus of this thesis, belong to Classical IBP. DLC is a utility-sponsored demand response program that allows a utility or a DR aggregator to cycle specific appliances of their customers on and off or implement thermostat setback during peak demand periods (Albadi & El-Saadany, 2008). In exchange, participating customers are entitled to financial incentives or discounted electricity bills. The aggregator works with users whose individual loads and curtailment potential is too small to be of direct interest to the buyers, such as residential customers.

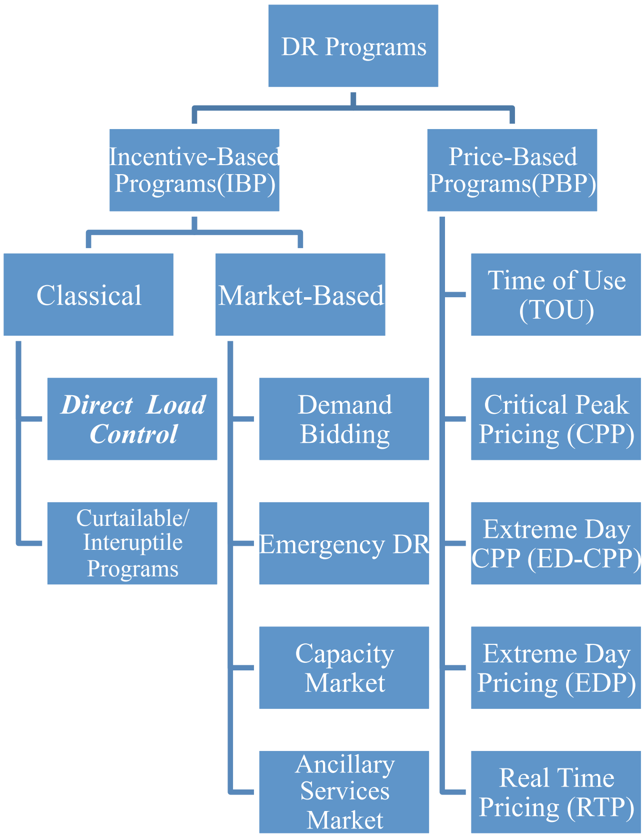


Figure 1-3 Classifications of DR programs (adapted from Albadi & El-Saadany, 2008)

1.3. Universities as Large Institutional Electricity Consumers

Although household air-conditioning makes the largest contribution to the peak demand in NEM, targeting their use does not automatically guarantee the most effective solution. When demand is at its maximum, any source of demand reduction can potentially relieve network congestion. As stated by Charles River Associates, in evaluating feasible demand management options:

> … [demand management] does not need to come from an end use that is causing peak demand to grow. Rather, any end-use load that can be reliably reduced when the network area experiences a peak is useful … (CRA, 2004)

The majority of activities aiming at reducing peak load in Australia are targeting the commercial and industrial sectors, simply because they are logistically easier to address than the residential sectors (National Appliance and Equipment Energy Efficiency Committee and the Australian Greenhouse Office, 2004). Universities are large electricity consumers in the commercial sector. Although it is hard to tell how much the Australian universities have contributed to the peak demand on summer extreme days for the whole commercial sector, it is true that many universities have difficulties coping with peak load problems. Figure 1-4 illustrates the annual electricity consumption for one of the large universities in Sydney, Australia from 1998 to 2011. It can be seen that total energy consumption is about 70,000 MWh to 90,000 MWh per annum, and of that, the off-peak use only accounts for approximately 40%, while shoulder and peak use making up the remainder.

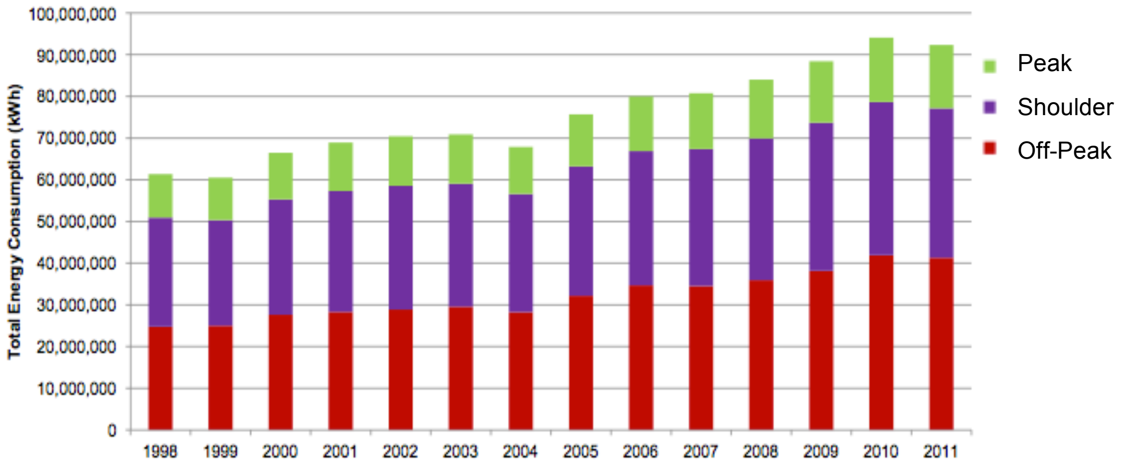


Figure 1-4 Annual electricity consumption profile of a university in Sydney, Australia (Campus Infrastructure & Services, 2012)

To meet their peak demand, universities are required to pay substantial penalty rates. According to the network price list of the electricity provider for the university in Figure 1-4, customers with a load of 750 MWh per annum or above will automatically be charged the kVA Demand Time-of-Use System ($10.23/kVA). The peak demand used to apply the charge is the highest 30-min peak demand in the preceding 12 months. Often these events may only occur for a few hours in a year, but penalty rates can account for up to 20% of electricity costs for a whole year.

1.4. Aims and Scope of the Research

Before DLC can be considered as a viable option for large institutional consumers, they have to understand what the impact will potentially be on their core functions.

The aims of this research are to explore the effects of various DLC air-conditioning strategies, in particular duty cycle restriction approach on university students' thermal comfort and cognitive performance. Results from this study will provide a rational basis for implementing DLC air-conditioning strategy in university buildings, without jeopardizing students' thermal comfort or learning performance.

The thesis comprises seven chapters:

Chapter 1 is an introduction of the research problem and its background—the increasing numbers of heatwave days and the concomitant peak demand problems caused by sharp increase of air-conditioning usage. Universities are levied substantial penalty rates to meet their peak electricity demand.

Chapter 2 reviews the literature related to this research topic. First, current DLC programs or trials offered by utility companies in the US and Australia are reviewed and compared, giving particular attention to thermal comfort related issues in these DLC studies. Second, previous thermal comfort studies on thermal transients (temperature cycles, ramps and drifts) are also reviewed and interpreted in the context of cutaneous thermoreceptor functioning and the spatial alliesthesia hypothesis. Third, cognitive performance studies under heat/cold stress, moderate thermal environments and thermal transients are also reviewed.

Chapter 3 presents the methods adopted in this research. Computer simulation is employed to simulate thermal environments inside a typical Australian university lecture theatre during various DLC events. Then, by applying the approaches to design of experiments (DOE), specifically the *orthogonal array* method, eight representative parameter combinations were selected from the simulation results for human subject experiments, in which thermal comfort surveys and cognitive performance tests were administered to subjects. Multilevel linear modelling was adopted to analyse the experimental data.

Chapter 4 to Chapter 6 report the results from computer simulation and laboratory experiments. Chapter 4 explores thermal environments and thermal comfort impacts of DLC events induced by various off cycle fractions, cycling periods, cooling setpoint temperatures, building envelope thermal performance and ventilation rates in 48 simulation cases. Chapter 5 analyses the results from two laboratory experiments comprising 6 DLC conditions and 2 control conditions, focusing on the association of both thermal sensation and thermal acceptability with main environmental and demographic factors. Chapter 6 presents results of experimentally induced DLC temperature fluctuations affect university students' cognitive performance in lecture theatres in terms of four generic cognitive skills of memory, attention, reasoning and planning.

Chapter 7 presents the conclusions from the research project.

2. Literature Review

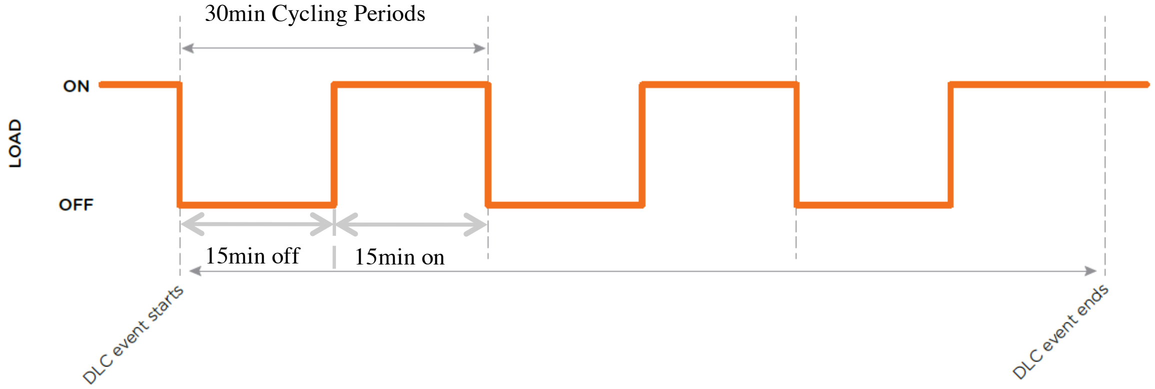
This chapter reviews the research literature related to the research topic. First, experience and learnings from actual DLC programs and trials offered by utility companies in the USA and Australia are reviewed and compared, giving particular attention to thermal comfort related issues. Second, thermal comfort standards and previous thermal comfort studies on thermal transients (temperature cycles, ramps and drifts) are also reviewed and interpreted in the context of thermoregulation control mechanisms. Third, human cognitive performance studies under heat/cold stress, moderate thermal environments (steady) and thermal transients are also reviewed. Last, by summarizing the previous literature, the specific research questions for this study were presented.

2.1. DLC Air-conditioning Programs and Related Thermal Comfort Issues

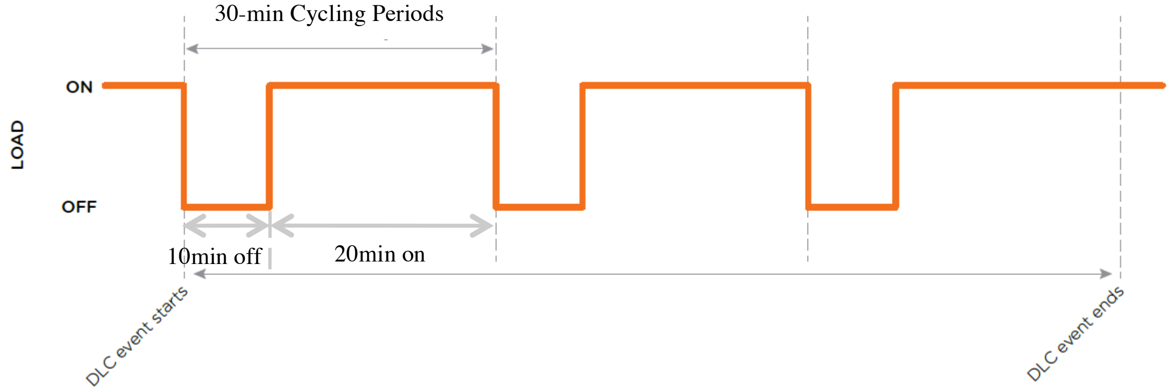
The most commonly targeted appliances in DLC programs are air-conditioners, electric water heaters and pool pumps. Air-conditioners are the focus of the present study.

2.1.1. Typical DLC control approaches

In this section, typical HVAC control approaches, namely duty cycle restriction and thermostat setback (Weller, 2011), are discussed and compared. Duty cycle restriction involves cycling the compressor of AC on and off at predetermined intervals during the summer peak time (Weller, 2011). Under this cycling program, the thermostat setting is maintained, but the AC compressor is only allowed to run for a predetermined time even if the setpoint is not met, and then switched off (with the fan on) for another fixed period. Off cycle fraction refers to the amount of time the AC compressor will be off during an activation period (Zhang and de Dear, 2015). Cycling period is the time for one complete cycle of AC compressor on and off (Zhang and de Dear, 2015). For example, 50% off cycle fraction with 30 min cycling period involves the compressor being switched off for 15 min and switched on for another 15 min in every half hour (Figure 2-1). This type of “cycling” control does not turn off the interior air distribution fan.



(a) 50% off cycle fraction with 0.5h cycling period



(b) 33% off cycle fraction with 0.5h cycling period

Figure 2-1 Illustration of duty cycle restriction approach

Thermostat setback approach directly adjusts the temperature setpoint of the AC thermostat, usually a smart thermostat (Weller, 2011). During the DLC event, the utilities control the smart thermostat to implement either a single-block temperature setpoint increase or a ramped setpoint increase to reduce AC electricity usage (Figure 2-2). Thermostat may turn off the interior air distribution fan just as it would under ordinary AC operation when the cooling setpoint is raised.

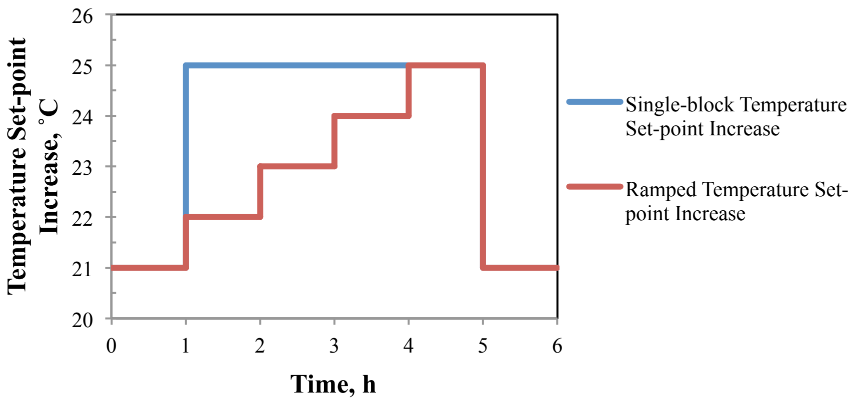


Figure 2-2 Illustration of single-block and ramped thermostat setback

DLC is the oldest form of dispatchable demand-side management. Many DLC systems that were launched as far back as the late 1970s remain in use throughout the United States (Weller, 2011). USA Utilities implemented DLC programs and interruptible/curtailable tariffs, both of which were in essence call options in which the customer sold the right but not the obligation for the utility to curtail or shed some of the customer's load in exchange for an up-front payment.

2.1.2. Current DLC air-conditioning programs

DLC AC programs in USA

In early 2012, E Source[1] investigated 49 utilities that run direct load control programs in 25 U.S. states and benchmarked 24 of those programs. The programs they assessed, which comprise 3,277 megawatts of available capacity and have nearly 2.8 million total participants, account for nearly 50% of direct load control participants and 45% of direct load control capacity in the US (E Source, 2015). To date, this study represents the most comprehensive and exhaustive set of data on DLC programs collected in the utility industry (E Source, 2015).

Figure 2-3 and Figure 2-4 demonstrate the participation rates of residential and small business customers in DLC programs offered by US utilities. Clearly, there are more DLC programs for residential customers than small business ones. The mean

[1] E Source provides independent research, advisory, and information services to utilities, major energy

participation rate for residential DLC programs (around 13%) also exceeds that in the small business one (8%).

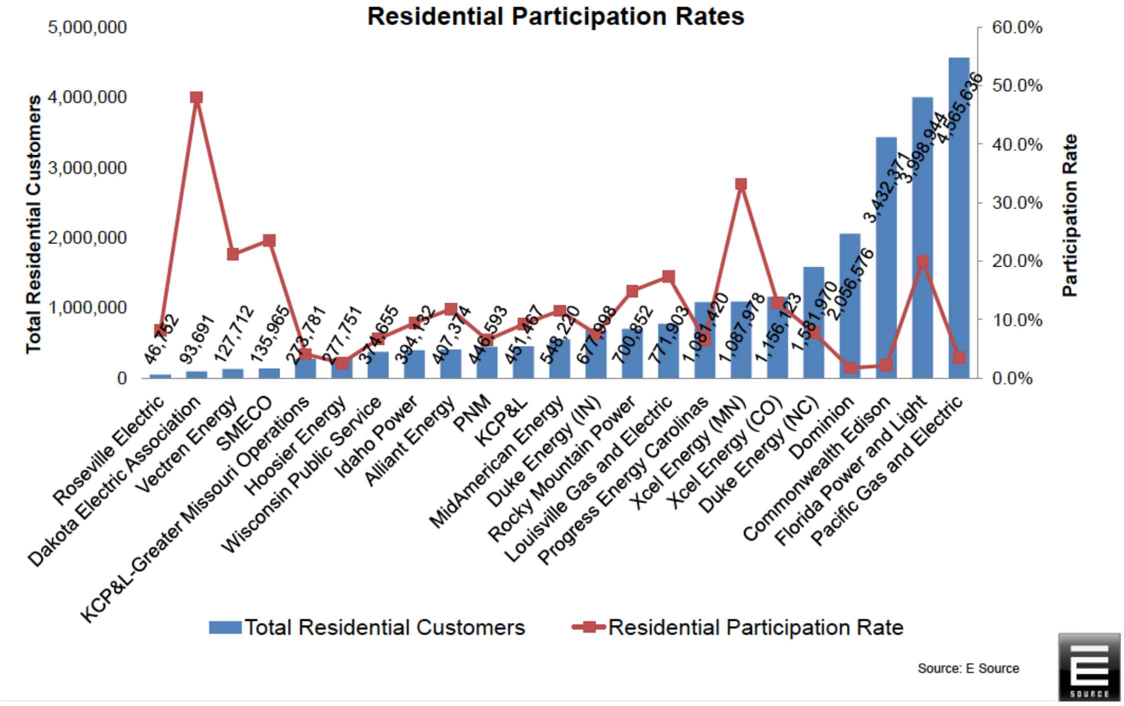
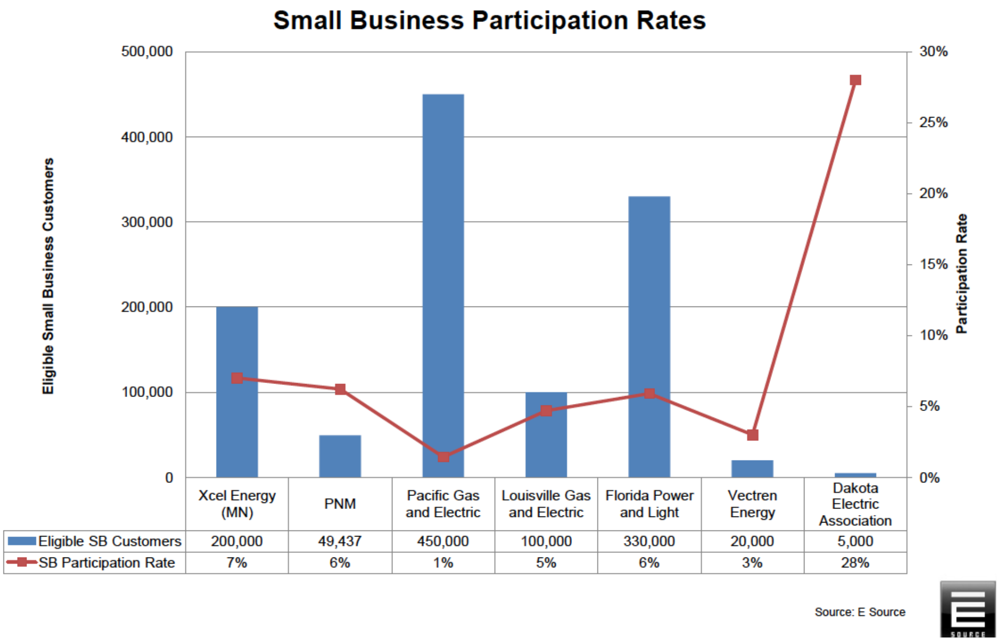


Figure 2-3 Participation rates of residential DLC programs in US utilities (Nelson, 2012)



	Xcel Energy (MN)	PNM	Pacific Gas and Electric	Louisville Gas and Electric	Florida Power and Light	Vectren Energy	Dakota Electric Association
Eligible SB Customers	200,000	49,437	450,000	100,000	330,000	20,000	5,000
SB Participation Rate	7%	6%	1%	5%	6%	3%	28%

Figure 2-4 Participation rates of small business DLC programs in US utilities (Nelson, 2012)

Table 2-1 summarizes 20 DLC AC programs currently offered by different utilities in the US. Different program specifications are also demonstrated in this table, which will be discussed in detail in the following.

Table 2-1 Summary of DLC AC programs offered by US utilities (not exhaustive)

Program names	**Eligible customers**	**Control devices**	**Off cycle fraction/ Thermostat setback**	**Event time may happen on**	**Event duration**	**Opt-out options**	**Incentives**
ComEd Smart Ideas® Central AC Cycling Program (ComEd)	Residential	AC control switches	50%, 100%	Weekdays (excluding holidays), 11 a.m. to 8 p.m.	50%—shut off for15 min every half hour; 100%—shut off for up to 3 hrs per day	Not mentioned	50%—$5/month (Jun–Sep); 100%—$10/month (Jun –Sep)
Con Edison Control your A/C remotely with a smart thermostat program (con Edison)	Residential, Business and Religious organization	Smart thermost ats	Not mentioned	When Con Edison needs to reduce electricity use	Not mentioned	Yes	$25 thank-you check for residential customers; $ 50 for business customers
Con Edison coolNYC Program (conEdison & ThinkEco)	Residential	SmartAC kit to connect AC to Wi-Fi	Not mentioned	3 to 5 times per summer	Up to 4 hrs	Yes	Enrolling earns 10,000 coolPoints; additional 5,000 coolPoints for every coolNYC event participated.
Southern California Edison Summer Discount Plan (SCE)	Residential and commercial	AC control switches	Residential 50%, 100%	Any time, usually 6 hours	50%—shut off for 15 min each half hour; 100%—shut off the whole event	Yes, can opt out for up to 5 days per summer	Non-override: up to $200/year for 100% cycling; up to $100 /year for 50% cycling
							Override: up to $100/year for 100% cycling; up to $50 /year for 50% cycling
			Commercial 30%, 50%, 100%		30%—shut off 9 min each half hour; 50%— shut off 15 min each half hour; 100%— shut off the whole event	Minimum 1-year commitment	30%—up to $20/year per unit; 50%—up to $90/year per unit; 100%—up to $250/year per unit
Pacific Gas & Electric Company SmartAC Program (PG&E)	Residential and business (no longer accepting new enrollments for businesses)	AC control switches (adaptive)	Residential 50%; Commercial 33%; Smart thermostats- max 4 degree increase	Up to 6 hrs per day between May 1 and October 31	Residential: shut off 15 min each half hour	Yes and without penalty (except an extreme emergency)	Residential: $ 50 one-time payment
		Smart thermost ats					
San Diego Gas & Electric Summer Saver Program (SDG & E)	Residential and business	AC control switches	Residential 50%, 100%	2–4 hrs per event; up to 15 days between May and October	30%—shut off for 30% of the hour previous to the event; 50%—shut off 50% of the hour previous to the event	Yes (but will not receive any incentive)	Residential: 50%—up to $11.5/ton per year; 100%—up to $30/ton per year.
			Business 30%, 50%				Business: 30%—up to $9/ton per year; 50%—up to $15/ton per year.
Baltimore Gas & Electric Co. PeakRewards SM A/C program (BGE)	Residential	AC control switches/ smart thermost ats	50%, 75%, 100% (Emergency Event)	When regional demand is close to surpassing regional supply	Not mentioned	No opt out for emergency event; up to twice per summer for non-emergency event	50%—$12.50 /month (first ear doubles); 70%—$18.75 /month (first ear doubles); 100%—$25.00/month (first ear doubles)
			Up to 50% (non-emergency event)	When the wholesale price of electricity is very high			
Florida	Residential	AC	Residential	Up to 6 hrs	50%—shut off 15	Yes	50%—$3/month (Apr-

Power & Light Company On Call® Program (FPL)	and business	control switches	50%, 100%	from Apr to Oct	min every half hour for up to 6 hrs; 100%—shut off for up to 3 hrs		Oct); 100%—$9/month (Apr–Oct);
			Business 50%, 75%		50%—shut off 15 min every half hour for up to 6 hrs; 100%—shut off 17.5 min every half hour for up to 6 hrs		$2/ton/month (Apr–Oct)
Public Service Electric and Gas Cool Customer Program (PSE&G)	Residential and small business	AC control switches/ Smart thermostats	50%	Weekdays, 1 p.m. to 7 p.m. from Jun to Sep	Shut off 10 min every 20 min; or 15 min every 30 min for up to 6 hrs	No	1. Residential Programmable thermostat: $50 one-time bill credit/ Cycling credit: $4/month (Jun–Sep) + $1/cycling event 2. Small business $7.5/month (Jun–Sep)
MidAmerican Energy Company SummerSaver℠ Program (MidAmerican)	Residential	AC control switches	100%	Weekdays (excluding holidays), 2 p.m. to 7 p.m. from Jun to Sep	Up to 5 hrs	Not mentioned	$40/year (first year); $30/year (following years)
Idaho Power A/C Cool Credit Program (Idaho Power)	Residential	AC control switches	50% to 65%	Weekdays (excluding holidays), 4 p.m. to 8 p.m. from 15th Jun to 15th Aug.	Shut off 15 min to 19.5 min every half hour	Yes, once a month	$5/month (Jun–Aug)
Alliant Energy Appliance Cycling program (Alliant Energy)	Residential	AC control switches	50%; 75% and 100% (Wisconsin only)	Weekdays (excluding holidays), 1 p.m. to 7 p.m.	Up to 6 hrs	Not mentioned	$32/year; additional $2/month if water heater is included in program
Dominion Smart Cooling Rewards program (Dominion)	Residential	AC control switches	50%	Weekdays (excluding holidays), 2 p.m. to 6 p.m. from Jun to Sep	shut off 15 min every half hour for 2–4 hrs	Yes, twice per summer	$40/year
Kankakee Valley REMC PowerShift AC Switch Program (Kankakee Valley REMC)	Residential	AC control switches	Not mentioned	Weekdays (excluding holidays), 4 p.m. to 7 p.m.	Up to 3 hrs	Not mentioned	$10/month (Jun–Sep)
FirstEnergy Easy Cool Rewards Program (FirstEnergy)	Residential	Smart thermostats	50%	Weekdays, 12 p.m. to 7 p.m.	shut off 15 min every half hour	Yes, once per summer	Nill
Duke Energy Power Manager Program (Duke Energy)	Residential	AC control switches	Two cycling options	Weekdays, in the afternoon to early evening, from May to Sep	turn off-and-on a portion of each half hour for 2–3.5 hrs	Yes, once per summer	One-time $25 or $35 installation credit + annual minimum of either $5 or $8 credits for each event
Xcel Energy Saver's Switch® Program (Xcel)	Residential and business	AC control switches	Not mentioned	2 p.m. to 7 p.m.	Turn off-and-on a t 15–20 min intervals for an average of 4 hrs	Minimum 1-year commitment	Residential: save 15 percent on their June through September electric energy charges Business: $2 /ton/month (Jun–Sep)
Pepco DC Energy Wise Rewards™ Program (Pepco)	Residential	AC control switches/ Smart thermostats	50%, 75%, 100%	Weekdays, 12 p.m. to 8 p.m., Jun to Oct	50%—shut off 15 min each half hour; 75%—shut off 22.5 min each half hour; 100%—shut off the whole event	Yes, twice per summer; minimum 1-year commitment	50%—$30/year + $30 one-time installation payment; 75%—$45/year + $45 one-time installation payment; 100%—$60 + $60 one-time installation payment
Entergy Summer Advantage Program (Entergy)	Residential	AC control switches	50%, 75%	Weekdays (excluding holidays), 12 p.m. to 7 p.m., Jun to	50%—shut off 15 min each half hour; 75%—shut off 22.5 min each half hour; for no more than 4	Yes, twice per summer	50%—$25/year + $50 one-time installation payment; 75%—$40/year + $40 one-time installation payment

				Sep	hrs		
AEP Appalachian Power Residential Peak Reduction Program (AEP Appalachian Power)	Residential	AC control switches	50%	Weekdays (excluding holidays), 12 p.m. to 8 p.m., May to Sep	Up to 6 hrs	Yes, once per summer for non-emergency event; minimum 1-year commitment	\$8/month (May–Sep)

- Target customers

The earliest DLC programs are carried out in residential buildings. Figure 2-3, Figure 2-4 and Table 2-1 reveal that until now, residential customers are still the main targets addressed, though several utilities also include commercial customers, or even religious organizations (Con Edison).

- Control devices

There are two types of AC control switches in use in DLC programs. The simple AC control switch is a basic, often one-way radio communicating equipment that has been used in DLC programs since early 1970s (Weller, 2011). This control switch is connected to load control receivers at utility premises. When it receives a radio signal from there, it starts the cycling process, which turns the air-conditioning compressor off and on for short periods of time. The specifics of how the switch controls the AC compressor determine the effectiveness of switches with regards to both load reduction and customer comfort. This control device is widely in use in the DLC programs from Table 2-1.

The simple switches generate load reduction by directly controlling the specific run-time of the AC compressor, i.e. 15 min in every 30 min. However, due to oversizing or mild weather, many ACs are *naturally* operating in duty cycles that are less than 100%. Thus, an AC unit running at a *natural* 70% duty cycle that receives a 50% off cycle fraction from the control switch will only drop to a 50% duty cycle instead of a 35% one. Consequently, the existence of the AC natural duty cycle has limited the load reduction potential from a DLC event using a simple switch.

The *adaptive switch*, which enables load reduction according to the AC's true duty cycle, is a new and sophisticated generation of switch control technology. The adaptive switch has the capability of “learning” from the observed duty cycle on designated days that have the characteristics of potential event days, and applying the chosen level of control (off cycle fraction) to this expected duty cycle. This new technology has now been deployed in PG & E SmartAC^{TM} Program (PG & E, accessed 23-03-2016).

Apart from the simple and adaptive control switches, there is a new control technology in use in the DLC programs—the smart thermostats or programmable communicating thermostats (PCT). Most PCTs can implement both duty cycle restriction (simple or adaptive cycling) and thermostat setback. The remote programming function of PCT will allow customers to adjust their thermostat settings without being there.

As can be seen from Table 2-1, AC control switches (simple) are still dominant control devices used by utility companies, although some offer their customers a choice between a control switch and a smart thermostat, or only a smart thermostat (Con Edison, accessed 23-03-2016). From a process evaluation perspective, both the AC control switches and the smart thermostats have their advantages and disadvantages (Table 2-2).

Table 2-2 Comparison of different load control devices (KEMA, 2010)

Load control device	Advantages	Disadvantages
AC control switch	Relatively inexpensive equipment	Cannot be marketed as product that could potentially improve home comfort or energy savings
	Installation can be done more quickly with lower technical skills	
	Home or business entry not needed for installation	
Smart thermostat	Is viewed as product that could potentially improve home comfort or energy savings by some customers currently without programmable thermostats	Relatively expensive equipment
	With enhanced features, could be used as home energy communications and control device	Installation takes longer and requires higher technical skills
		Home or business entry needed for installation

- Off cycle fraction/ thermostat setback

Most DLC programs in Table 2-1 offer multiple off cycle fractions, allowing customers to move from one level of control to another and determine which option works best for them. The DLC event usually happens on weekdays (excluding holidays).

The duration can range from 2–6 hours. For both residential and commercial customers, 50% off cycle fraction with a 30 min period is the most commonly adopted DLC algorithm, meaning that AC is cycled on and off at 15min intervals during a load control event. Other cycling options include 30%, 33%, 65%, 75% and 100% (all with 30min cycling period). For 100% off cycle fraction, the AC compressor will be off for the whole duration of the DLC event. The off cycle fraction offered for commercial customers are generally lower than residential customers (SCE, PG&E, SDG&E and FPL, accessed 23-03-2016). For smart thermostat users, the setpoint setback (increase) does not exceed 4 °C (PG&E, accessed 23-03-2016).

- Opt-out options

Many utilities offer their customers the "opt-out" choices, meaning that if customers don't want to participate in a specific DLC event or they do not feel comfortable, they can choose to opt out. However, this option generally can only be used for limited times (such as once or twice per summer); otherwise the promised incentives might be reduced or even cancelled. Customers use this option for varied reasons, such as health concerns, devices are activated too often, incentives are not large enough or any other inconveniences that DLC events may have caused; yet *discomfort*, was cited most often as the reason why opt-out is used (KEMA, 2010). Researches also reveal that opt-out rates increase as the length of DLC event duration increases (Greenberg and Straub, 2008; KEMA, 2006; Egan-Annechino et al., 2005), which is presumably caused by discomfort. Above facts suggest that there is a limit on how long occupants will tolerate deviations from preferred conditions, and a consequent limit on the persistence of load reductions (Newsham & Bowker, 2010).

- Financial incentives

Table 2-1 also shows different levels of incentives given to the customers for participating in the DLC program. Most programs provide customers with a monthly/yearly bill credit, while others send customers a one-time sign-on "thank you" payment when they join the program. There are also programs that combine the one-off payment with the monthly payment or even "pay as you go" with the individual DLC event. While the one-time check pays participants only once, the monthly and yearly bill credits are given to participants each year they participate in the program. The incentive levels also differ from the off cycle fractions the customers opt for, the size of the customer's air-conditioning equipment, the frequency of the cycling plan and opt-out options.

DLC AC programs in Australia

In contrast to the US where DLC AC programs are readily available in a large number of utility companies, Australia is still at the early stage of implementing DLC. Beginning from 2006, several utility companies, such as ETSA Utilities, Endeavour Energy (operating as Integral Energy), Western Power and Energex, have conducted pilots and trials of DLC of air-conditioners in the residential sector. Results from the trials suggest that a major reduction in the normal AC peak load may be achievable—approximately 20%–30% reduction of the peak demand in the trial households (Futura Consulting, 2011). Some network businesses are now introducing direct load control options into their customer offerings.

Since 2006, ETSA Utilities has conducted several direct load control trials targeting residential and commercial customers' air-conditioning. Results of these trials indicated that the potential reductions in peak load range from 19% to 35%. Customers were offered a one-off incentive payment of AU$100 to participate. The trials involved the air-conditioners being cycled 15min off every 30min over a 3.5–4 h period (ETSA, 2008).

Endeavour Energy (Integral Energy) implemented a residential air-conditioner DLC trial in 2007 as part of the Blacktown Solar City project. The trial achieved a 27% reduction in peak demand. Air-conditioners were cycled between 1pm and 8pm on event days. Participants received a $25 credit on their bill at the commencement of the trial and $75 at end of the trial (Sayeef et al., 2013).

Western Power launched an air-conditioner DLC trial in 2010 as one of the initiatives in the Perth Solar City project. Participants were offered an annual rebate of $100 for the first year and $200 for the second year to increase take-up. The trial adopted a 15min on/off cycle that lasted for 3–4 h. The trial involved 203 residential participants over the first summer and is targeting a total of 375 participants over the two-year trial period (Perth Solar City Annual Report, 2012).

Energex's *Cool Change* DLC Trial, implemented from 2007 to 2011, involves trialling direct load control of over 2,000 customers' air-conditioners in suburbs across Brisbane. On average, participating customers reduced their demand by 17% over the 2007–2010 summer peaks. Participants received their $100 gift voucher upon successful installation of a device. They also received cash incentives from $30 to $50 according to the number of air-conditioners included in the trial (Futura Consulting, 2011).

2.1.3. Thermal comfort issues in previous DLC studies

Most previous DLC studies carried out by utilities (Table 2-3, DLC studies listed are representative rather than comprehensive) did not address participants' thermal comfort issues as a primary concern. As is shown in Table 2-3, 4 programs out of 7 have carried out direct comfort surveys to their customers; 3 other programs only investigated participants' over-ride rate or complaints customers have lodged during the events. For the former, the four programs have all carried out the so-called *"satisfaction" surveys*[2], in which occupants are directly asked whether they are satisfied or comfortable during DLC events. However, compared to a *"right-now"* or *"point-in-time" survey*[3], the "satisfaction" survey covers much longer period so the "overall" survey result may not be representative of occupants' instantaneous thermal response; meanwhile it is not possible for researchers to correlate thermal comfort with environmental factors using these survey results.

[2] "Satisfaction" surveys are used to evaluate thermal comfort response of the building occupants in a certain span of time (ASHRAE 55-2013).

[3] "Right-now" or "point-in-time" surveys are used to evaluate thermal sensations of occupants at a single point in time (ASHRAE 55-2013).

Table 2-3 Thermal comfort issues addressed in previous DLC studies (studies listed here are not exhaustive)

DLC Programs or Trials	Country	Year	Customer Segment Addressed	Load Control Method	Off Cycle Fractions	Cycling Periods	DLC Event Duration	Customer Feedback on Comfort	References
Con Edison's Central AC Program & Small Commercial DLC Pilot Program	USA	2002 – 2004	Residential and small business	Duty cycle restriction/ Thermostat setback	50%	4 °C	4 hrs	Over-ride rate 27%	Egan-Annechino et al. (2005)
ETSA Utilities Residential direct load control Trial	Australia	2005 – 2008	Residential	Duty cycle restriction	25%, 50%	0.5h, 1h	1–3 hrs	No customer complaints	ETSA (2008)
BGE Demand-Response Infrastructure Pilot	USA	2007	Residential	Duty cycle restriction	30%, 50%, 75%	0.5h	4–5 hrs	"Comfort issues due to cycling were not a major concern"	Greenberg and Straub (2008)
2008 SDG&E Summer Saver Program	USA	2008	Residential and business	Duty cycle restriction	Residential: 50%, 100%; Business: 30%, 50%	—	2–5 hrs	47% of residential participants were uncomfortable; 87% of the residential dropouts and 89% of the commercial dropouts were uncomfortable.	KEMA (2009)
2010 Hydro Ottawa Peaksaver® Program	Canada	2010	Residential and small business	Duty cycle restriction/ Thermostat setback	30%, 50%	Not stated	Up to 4 hrs	12%–17% discomfort	FSC (2011)
Perth Solar City Air-conditioning Trial	Australia	2010 – 2012	Residential	Duty cycle restriction	33%, 50%	0.5h	Up to 4 hrs	76% of participants felt "no change" in comfort levels	Perth Solar City Annual Report (2012)
2014 PG & E SmartAC Program	USA	2014	Residential and small business	Duty cycle restriction (simple and adaptive switch)	33%, 50%	0.5h	Up to 6 hrs	32% discomfort vs. 23% for control group	Nexant (2015)

It is natural that peak load savings through DLC programs are the primary concern of utility companies; yet these savings should not and cannot be achieved at the great cost of occupants' thermal comfort. In effect, customer's perception of discomfort is a direct *constraint* on program implementation and thus on potential load savings. Here is what happened after BGE initiated an emergency DLC event during the heatwave day in 2011:

> Friday's intense heat led to the first "emergency event" in the four-year-old program, lasting about six hours. Participating customers came to a slow boil as they couldn't override the shutdown, and with no air-conditioning for up to 10 hours, watched the thermostats in their homes top 90 degrees (32.2 °C). (Siegel, 2011)

> As consumer advocates called for a review of BGE's PeakRewards program, the utility said Monday that more than 3,800 customers have dropped or modified their participation (reduced their level of cycling) after seeing air-conditioners cycled off for hours Friday—the hottest day in 75 years. (Kay and Boughman, 2011)

The above is an example of how badly customers' discomfort could affect the effectiveness of DLC programs. Generally speaking, previous DLC trials or programs found that the managed use of the compressor and power supply to an air-conditioner has little impact on customer comfort levels if the off cycle fraction is between 50% and 67% (Futura Consulting, 2011). The following section summarized common methods used in previous DLC programs (studies) that included investigations of customers' thermal comfort.

Methods of Comfort Studies in DLC Programs

According to different ways that participants' thermal comfort data are collected, commonly used methods range from post-event survey to daily log; regarding the research objects addressed, methods include single sample survey and control group method.

- Post-event survey vs. daily log

In DLC studies, the most commonly used method to investigate participants' comfort is through post-event surveys. The surveys are usually conducted a few days after a DLC event so that participants' memories are still fresh. Survey questions might include drivers of participation, marketing and program information, switch use/thermostat use, program enrolment, control device installation, satisfaction with incentives, program in general, etc. (KEMA, 2010), among which thermal comfort during the event is only one aspect.

The most commonly used post-event survey questions to address participants' thermal comfort during DLC events are: 1) whether the participants were aware of the DLC events; 2) whether those who noticed the DLC events reported being uncomfortable (KEMA, 2010). Another frequently used predictor of discomfort is override rate or opt-out rate, as override behaviour is mostly triggered by thermal discomfort (KEMA, 2010).

Table 2-3 demonstrates that DLC programs that have not conducted direct comfort surveys can employ override rate as a discomfort predictor. Other comfort-related survey questions include whether the experience of the DLC event was better or worse than customers had expected; how likely they are to opt out of future DLC events (PG&E, accessed 23-03-2016), whether they have considered leaving the program as a result of the interruptions of the past summer (SCE, accessed 23-03-2016) and their willingness to switch to more intense cycling options (SDG&E, accessed 23-03-2016), etc.

As the post-event survey requires much recall of the control events, the accuracy and reliability of the survey questions is dubious. Compared to a post-event survey, a daily log might be more reliable since much less recall is required for logs (Kempton et al., 1992). However, daily logs require more recording effort, and can have a large fraction of missing data.

- Single sample survey vs. control survey method

Figure 2-5 is an example of a single sample survey—each program investigates the discomfort rate of its DLC event participants only. This method is simple and easy to carry out, and the results can be compared between different programs. However, a drawback of this method is that the reported discomfort did not completely stem from the DLC events. Actually on a hot day, customers might report discomfort even without any DLC events. In order to properly quantify the amount of discomfort deriving only from the DLC events, it is necessary to adopt a control survey method.

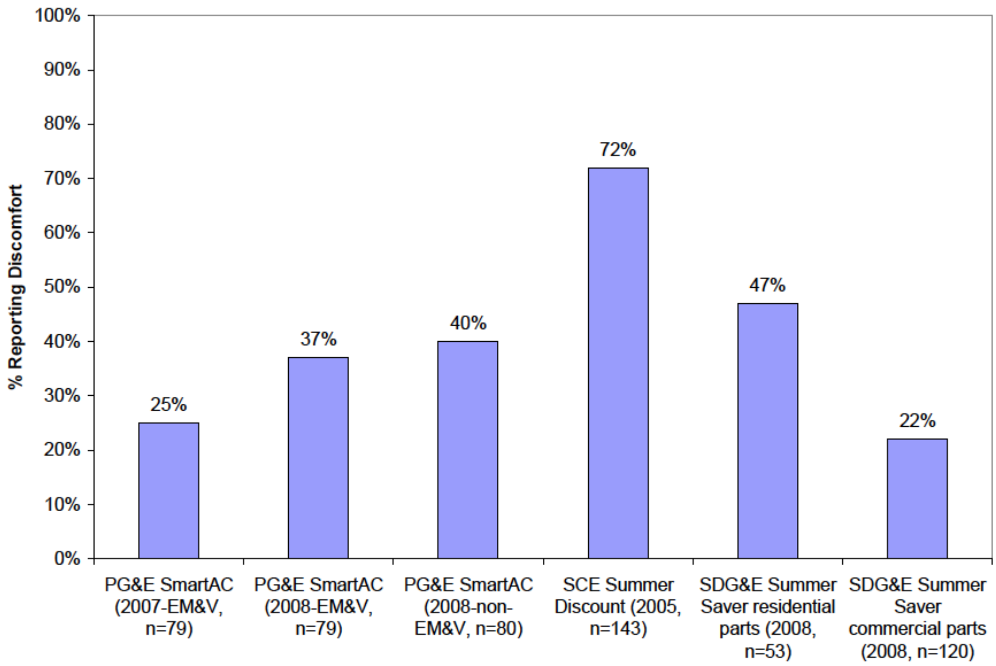


Figure 2-5 Percentage of participants noticing the events who reported discomfort during DLC events (KEMA, 2010)

Technically, the control survey method comprises two separate surveys—one for customers who have experienced the DLC event (treatment group) and the other surveys for those who have not (control group). The purpose of the second survey is to provide a baseline level of hot-day discomfort in order to judge customer discomfort specifically caused by DLC events. Since the outdoor weather has a great impact on customers' thermal comfort, the disadvantage of this method is that to accurately specify the baseline hot-day discomfort, weather conditions on a DLC event day and a control day must be identical or extremely similar. However, it is very hard to find such a day.

Setting 2010 Hydro Ottawa peaksaver® Pilot Program (FSC, 2011) as an example, the DLC event day was 4th Aug and the control day was selected to be 7th Sep. Figure 2-6 illustrated that the control-day temperatures were noticeably different than the event-day temperatures. Although average temperatures during the DLC event hours (2 pm to 6 pm) for both days were fairly close, but the earlier part of the day was much warmer on the event day than on the control day, which expectedly affected customers' comfort levels during DLC events.

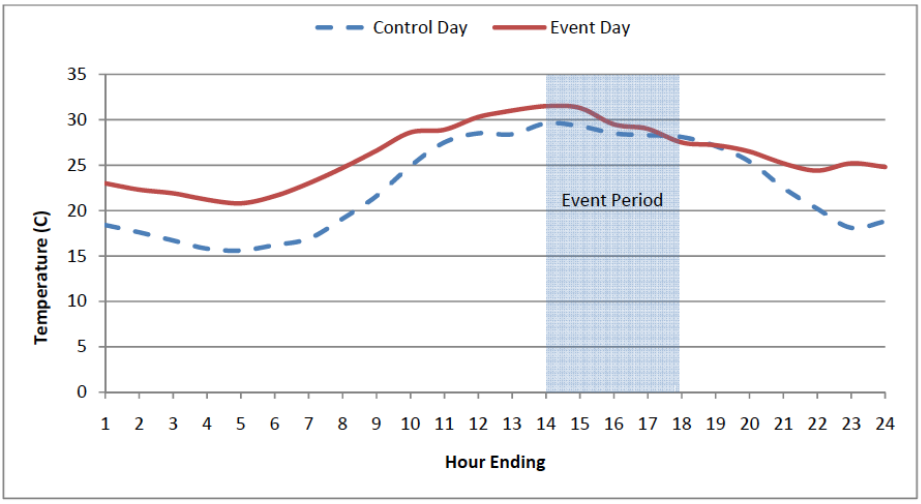


Figure 2-6 Toronto temperatures on DLC event day and control day (FSC, 2011)

During the surveys, customers who reported discomfort were asked to specify when the discomfort started and ended. For any given hour, the total fraction of customers reporting discomfort on the control day is lower than the event day (Figure 2-7).

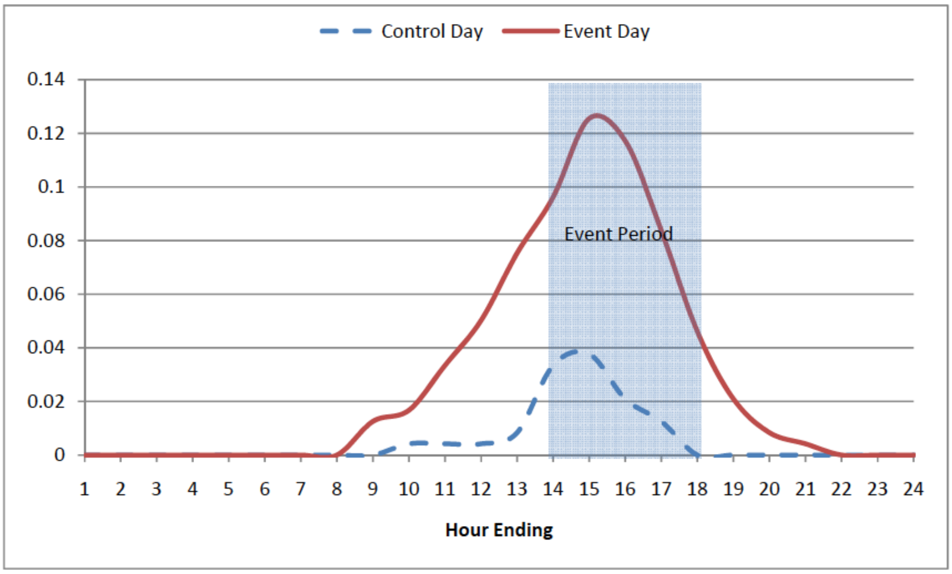


Figure 2-7 Percentage of Toronto Hydro customers reporting discomfort during each hour (FSC, 2011)

Other comfort-related indicators

To study discomfort issues in DLC programs, some researchers have developed specific indicators; relations between thermal comfort (discomfort) and several program variables were also examined.

- *Discomfort-From-Cycling* Index

In Atlantic Electricity Company Pilot DLC Programs (Kempton et al., 1992), a *Discomfort-From-Cycling Index* (*DI*) is employed to differentiate the degrees to which cycling programs increased customers' discomfort. The discomfort index is expressed as Equation 2-1:

$$DI = f_{\text{cycled}} - f_{\text{non-cycled}} \qquad \text{Equation 2-1}$$

Where f_{cycled} is the proportion of days that each house reported insufficient cooling during the cycled days, where $f_{\text{non-cycled}}$ is the fraction of days that each house reported insufficient cooling during non-cycled days. Thus, DI = 0 means that cycling events do not affect comfort; DI = 1 means that cycling events always reduce comfort; DI = -1 denotes that cycling events always promote comfort (not likely to happen). Compared with a simple calculation of f_{cycled}, the benefits of the discomfort index are that it only becomes positive if the fraction of discomfort days is higher during cycling periods. Thus, people who are always complaining will have an index of 0, implying no change of discomfort.

- Indoor temperature increase & thermal comfort

In Atlantic Electricity Company Pilot DLC Programs (Kempton et al., 1992), researchers also calculated the reported interior temperature increase due to cycling ΔT. ΔT is taken from the daily logs of afternoon temperatures and expressed as Equation 2-2. Thus, positive values represent the expected direction of higher interior temperatures on cycled days.

$$\Delta T = t_{cycled} - t_{non-cycled} \qquad \text{Equation 2-2}$$

where t_{cycled} refers to the average reported temperature on the cycled days and $t_{non-cycled}$ refers to the average reported temperature on the non-cycled days. Positive

ΔT values denote higher interior temperatures on cycled days, which are expected to happen.

Figure 2-8 plots the relationship between temperature increase ΔT and discomfort index DI. The majority of points congregate on the DI scale of 0, meaning that most of the participating households reported no change of the discomfort level. Correlation analysis revealed that the discomfort index and the temperature increase were positively significantly correlated (R^2 = 0.23, p < 0.0001). So to speak, houses with increased interior temperatures during cycling events tended to report increased discomfort as well.

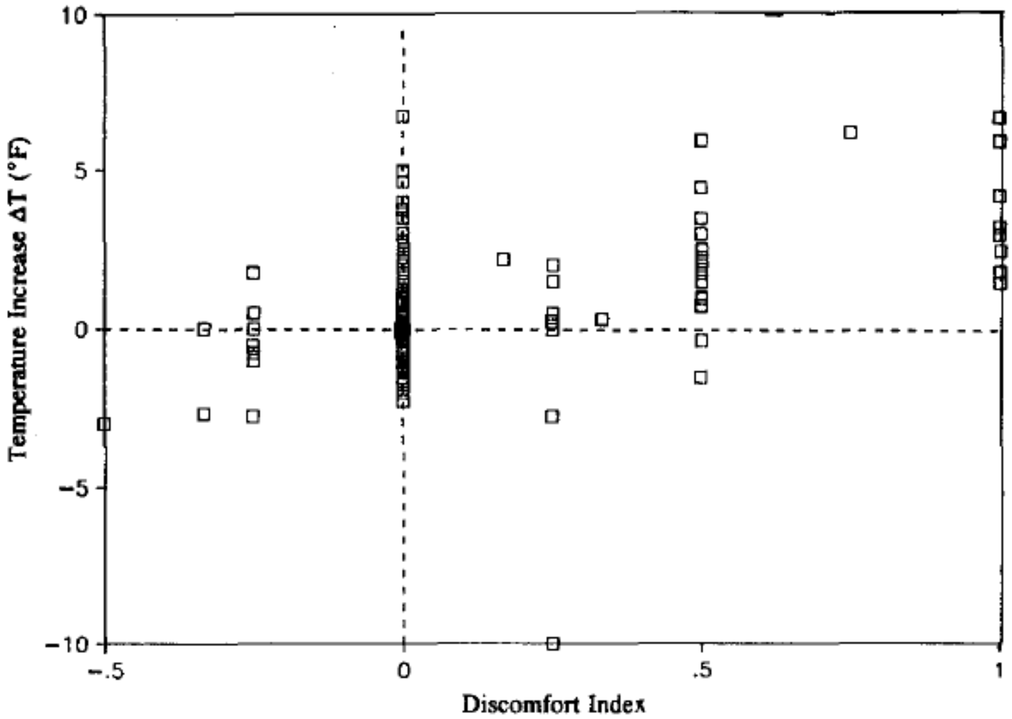


Figure 2-8 Temperature increase (ΔT) vs. discomfort index (DI) (Kempton et al., 1992)

- Off cycle fraction & thermal comfort

A few DLC studies have also examined the relationship between different off cycle fractions and participants' thermal comfort responses. For example, KEMA (2010) compared participants' discomfort rate under different off cycle fractions in two DLC programs—SCE Summer Discount (SCE, accessed 23-03-2016) and SDG&E Summer Saver (SDG&E, accessed 23-03-2016). The results were quite interesting: for both programs, participants have reported higher discomfort rate in DLC algorithms with lower off cycle fractions than the higher ones (Figure 2-9). It seems unreasonable that participants who had their AC shut off during the whole DLC event would feel more comfortable than participants who had their AC off for half of the time. KEMA (2010) has proposed two hypotheses as possible explanations: first, those who had selected milder cycling options did so based on their (weak) heat tolerance capacity; yet, they still found them intolerable. Second, participants who have selected intense DLC algorithms may simply not be at home as often. However, the second hypothesis was not supported by the data: for SCE programs, participants on the enhanced plan actually reported being home more often than participants on the base plan; for the SDG&E programs, there was no significant difference in percentage of participants staying at home during DLC events between 50% cycling options and 100% cycling options. The first hypothesis seems to be plausible. Besides, participants may also have been motivated by the higher financial incentives that the intense cycling options offered.

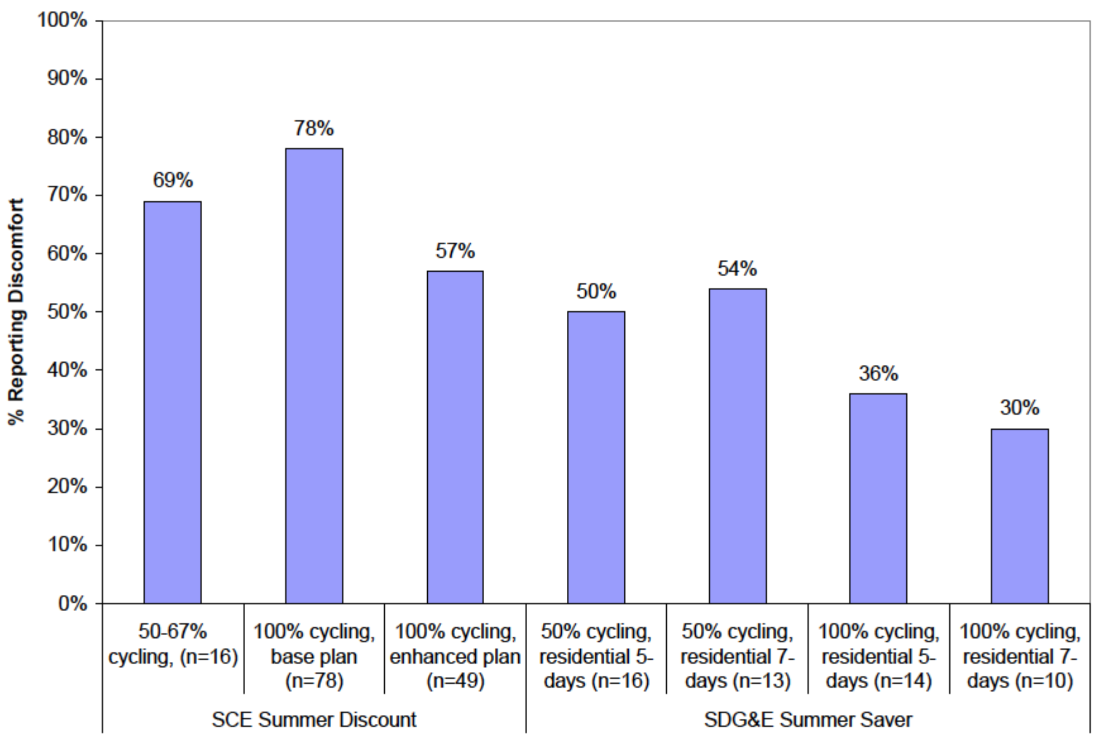


Figure 2-9 Percentage of participants reporting discomfort in SCE and SDG&E DLC program by various off cycle fractions (KEMA, 2010)

- Different control devices & thermal comfort

KEMA (2008, 2010) examined whether participants' discomfort during DLC events varied from type of control devices they were using (AC control switch vs. smart thermostat). Results found that participants who used AC control switches were much more likely to recall DLC events than participants who used smart thermostats. Regarding discomfort rate, there were 14% of smart thermostat participants reporting discomfort whereas 9% for switch participants. Yet, this difference was not statistically significant, meaning that control devices for DLC events will not make any difference in terms of participants' thermal comfort.

- Different thermostat setback approaches & thermal comfort

Ramped setpoint increase is a relatively new thermostat setback approach in DLC programs. The advantages of employing ramped over single-block setpoint increase lie in two aspects: first, the ramped setpoint increase can maintain a relatively constant level of load reduction through DLC events; second, it provides continuous cooling air to the participants (KEMA, 2008).

In 2007 PG&E SmartAC Program, the thermostat group implemented two different ramped setpoint increase strategies. The "steep" ramping strategy increased the setpoint by 1 F° at the beginning of each of the first 4 hours and maintained at that setpoint for the rest of the event duration. The "gradual" strategy, in comparison, increased the setpoint by 1 F° at the beginning of every 2 hours (Figure 2-10). KEMA (2008) have compared the peak load savings by these two ramping strategies, however did not provide any information on participants' thermal comfort responses under different ramping strategies.

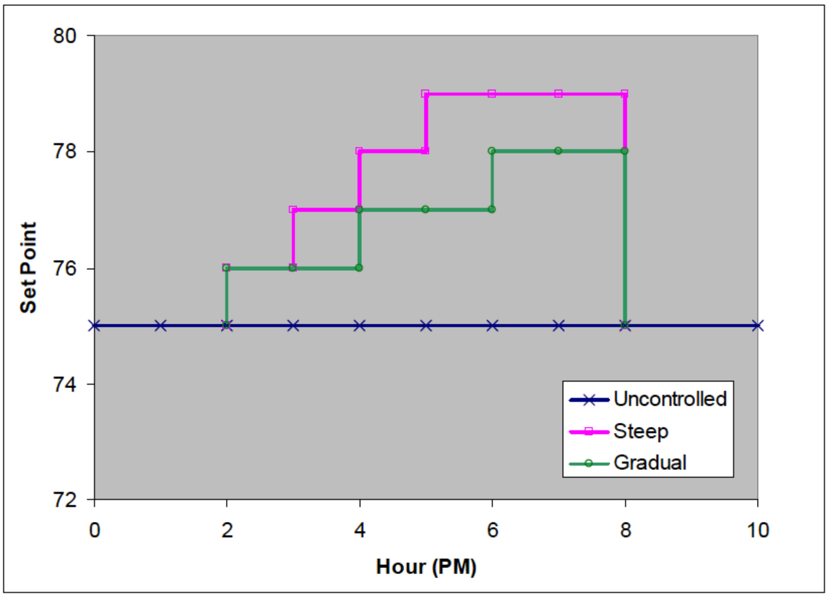


Figure 2-10 Comparison of two ramping strategies employed in 2007 PG&E SmartAC program (KEMA, 2008)

- Pre-cooling and ramping strategies & thermal comfort

Ward and White (2007) have carried out a “smart thermostat” control trials in the summer of 2007 in a commercial office building in Melbourne. A range of temperature setpoint control strategies was tested, including (i) simple temperature setpoint increase from 22.5 °C to 24 °C for 2.5 h (Figure 2-11), (ii) pre-cooling of 1.5 °C from 22.5 °C to 21 °C followed by temperature setpoint increase from 21°C to 24°C for 2.5 h (Figure 2-12), and (iii) pre-cooling of 1.5 °C from 22.5 °C to 21 °C for 2.75 h followed by ramped temperature setpoint increase of 1 °C every 30 min until reached 25 °C (Figure 2-13).

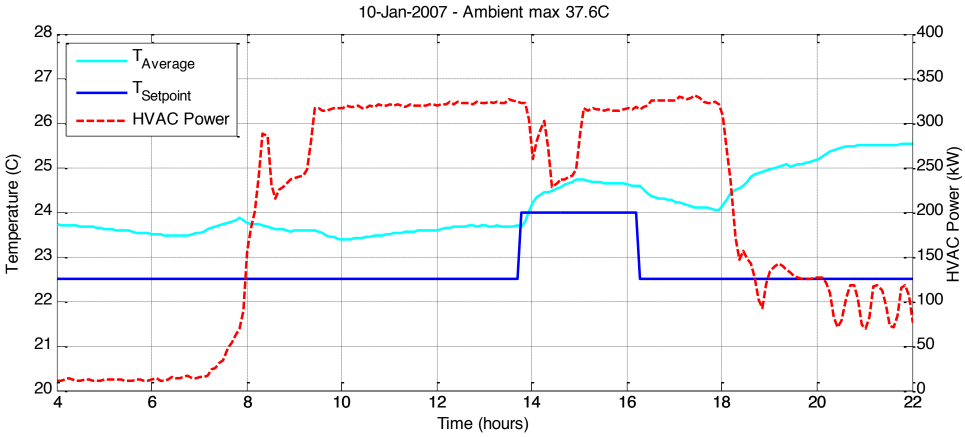


Figure 2-11 Single-block temperature setpoint increase (Ward & White, 2007)

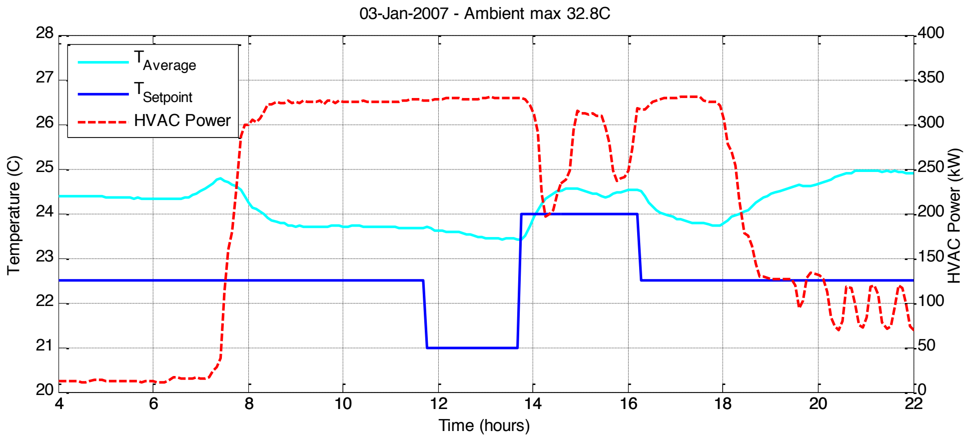


Figure 2-12 Pre-cooling followed by temperature setpoint increase (Ward & White, 2007)

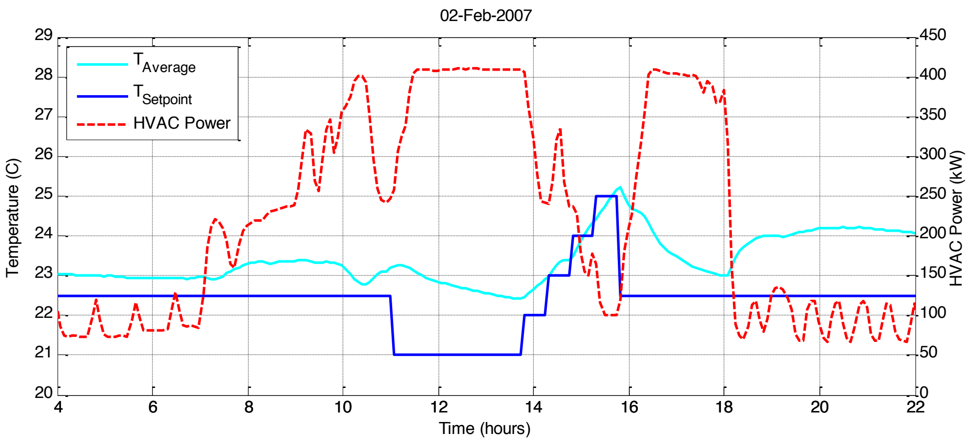


Figure 2-13 Pre-cooling followed by ramped temperature setpoint increase (Ward & White, 2007)

In the trial, the researchers have not conducted any detailed thermal comfort survey. Comfort feedback was supposed to be obtained by the usual complaint reporting mechanisms, however no feedback was received. This was deemed reasonable since all setpoints adopted in the trial fell within the ASHRAE recommended comfort range. However, one notable aspect of this trial was the different impacts of the pre-cooling had on individual zone temperatures. Since the HVAC system was already operating at full capacity, the pre-cooling was only able to cause a redistribution of cooling between zones. Figure 2-14 demonstrated that when the temperature setpoint for the building was reduced, the temperature in zone 22 went down as desired but the temperature in zone 42 increased. This phenomenon should deserve more attention when using the pre-cooling strategies since building occupants of zones with increased temperature would suffer from loss of comfort even before the DLC events began.

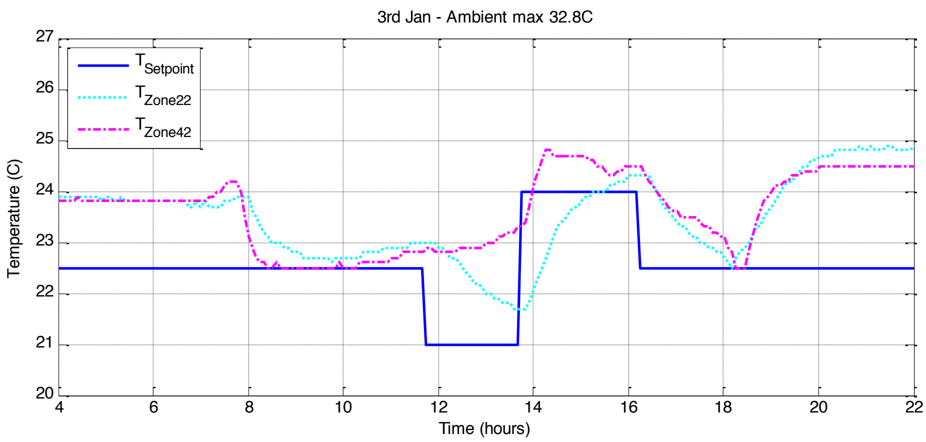


Figure 2-14 Temperature increase in Zone 42 due to pre-cooling (Ward & White, 2007)

2.1.4. General conclusions

Section 2.1 reviews the definition and classification of direct load control strategy, and its current development in the US and Australia. Direct load control is a utility-sponsored demand response program which allows a utility to cycle specific appliances on and off during peak demand periods. The most commonly targeted appliances in DLC programs are air-conditioners. Direct load control of air-conditioners typically consists of duty cycle restriction approach and thermostat setback approach; the former is the research interest of this study.

Until early 2012, there were already 49 utility companies running DLC programs in 25 US states. Yet in Australia, DLC was still at the early stage of development and several utilities have conducted pilots and trials of DLC of air-conditioners in the residential sector. Thermal comfort was not a primary concern in previous DLC programs, which have carried out, if any, "satisfaction surveys" to address thermal comfort issues. However, these surveys can only reflect occupants' overall impression or attitude on comfort rather than represent occupants' instantaneous thermal comfort during a DLC event. Analysis on comfort-related indicators only reflected general trends between thermal comfort (discomfort) and program variables; there is no analysis focusing on correlations between thermal comfort and environmental parameters during DLC events.

2.2. THERMAL COMFORT DURING TRANSIENT CONDITIONS

During summer peak times, direct load control of air-conditioners, no matter duty cycle restriction or thermostat setback approach is adopted, will cause air (operative) temperature fluctuations in participants' rooms. For the duty cycle restriction approach, cycling the AC compressor on and off for a given proportion of time in its duty cycle will generate repeated rises and falls in air (operative) temperature, thus form *temperature cycles*. Since this approach only controls the AC compressor rather than the indoor temperature, the fluctuation amplitude and rate of temperature change depend on the controlled AC compressor run-time, the outdoor temperature, building thermal performance, ventilation rate, etc. It is possible that the indoor temperature fluctuation amplitude exceeds the range of thermal comfort zones in steady states and potentially causes thermal discomfort for building occupants.

Thermostat setback approach adjusts the temperature setpoint of the AC thermostat either by a single block temperature setpoint increase or a ramped setpoint increase, and will cause monotonic, non-cyclic increment in operative temperature, forming *temperature ramps or drifts* (depending on whether the temperature change is actively controlled).

Temperature cycles and temperature ramps (drifts) are actually two types of *non-steady-state* conditions, with *temperature step-change* (also called transients by ISO 7730 (2005)) as a third one. In the following, relevant thermal comfort standards and important climate chamber studies on temperature cycles, ramps and drifts will be reviewed. The thermoregulation control mechanisms will also be reviewed.

2.2.1. Thermal comfort standards regarding temperature cycles, ramps and drifts

In ASHRAE 55 (2013), cyclic variations refer to "those situations where the operative temperature repeatedly rises and falls, and the period of these variations is not greater than 15 minutes". The maximum allowable peak-to-peak cyclic variation in operative temperature is 1.1°C. Temperature ramps and drifts are defined as "monotonic, non-cyclic changes in operative temperature" (ISO 7730, 2005; ASHRAE 55, 2013). Cyclic variations with a period greater than 15 minutes are also treated as ramps or drifts. The maximum change allowed for ramps and drifts in operative temperature during a period of time is shown in Table 2-4.

Table 2-4 Limit on temperature ramps and drifts by ASHRAE 55 (2013)

Time Period, h	0.25	0.5	1	2	4
Maximum Operative Temperature Change Allowed, °C	1.1	1.7	2.2	2.8	3.3

ISO 7730 (2005) defines temperature cycle as "variable temperature with a given amplitude and frequency". Unlike the corresponding definition by ASHRARE 55 (2013), the definition by ISO 7730 (2005) does not have any limit on cycling periods (frequency): "If the peak-to-peak variation is less than 1°C, there will be no influence on the comfort and the recommendations for steady-state may be used. Higher peak variations can decrease comfort". Definitions on ramps and drifts are the same as in ASHRARE 55

(2013). Also, ISO 7730 (2005) regulates that "if the rate of temperature change for drifts or ramps is lower than 2.0 °C/h, the methods for steady-state variation apply."

Figure 2-15 is a graphic comparison of limits or recommendations on temperature cycles, ramps and drifts by ASHRAE 55 (2013) and ISO 7730 (2005). It reveals that for temperature cycles, the recommended condition by ISO 7730 (2005) is more conservative than that by ASHRAE 55 (2013). For temperature ramps and drifts, ASHRAE 55 (2013) permits higher rate of temperature change than ISO 7730 (2005) standard when the frequency is greater than approximately 0.8 cycles/h whereas lower rate of temperature change when the frequency is less than 0.8 cycles/h. Generally speaking, ISO 7730 (2005) standard is more conservative in defining limitations for rapid temperature variations than ASHRAE 55 (2013).

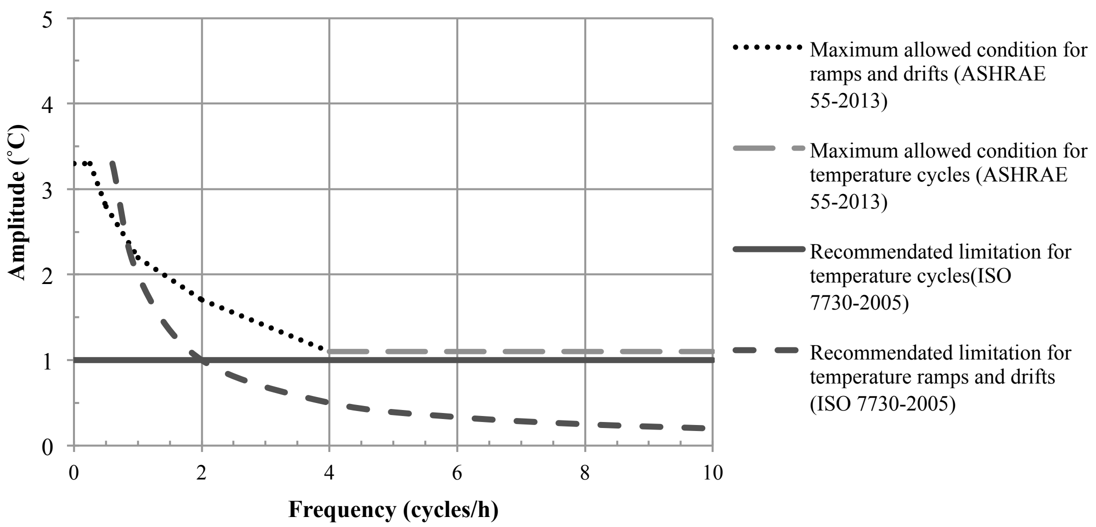


Figure 2-15 Graphic comparison of limits (recommendations) on temperature cycles, ramps and drifts by ASHRAE 55 (2013) and ISO 7730 (2005)

2.2.2. Thermal comfort studies on temperature cycles, ramps and drifts

Temperature Cycles

Hensen (1990) reviews 5 climate chamber experiments on cyclical temperature variations (Sprague and McNall, 1970; Wyon et. al., 1971; Wyon et. al., 1973; Nevins et. al., 1975; Rohles et. al., 1980). After this review, there has been no recent study on temperature cycles. Table 2-5 summarises their key experiment design parameters and main results. Regarding the range of comfort zone due to temperature variations, Table 2-5 reports inconsistent results from the experiments: Sprague and McNall (1970) reported narrowed comfort zones with increased rates of temperature change; Wyon et. al. (1971, 1973), nonetheless, found the opposite to be true—subjects tolerating greater amplitudes when the temperature changes more quickly; Nevins et al. (1975) and Rohles et al. (1980), however, concluded that fluctuation-induced comfort zones would not differ much from those obtained in steady state conditions. Possible explanations for these contradictions pointed out by Hensen (1990) related to distinct experimental designs, different voting scales, acceptability criteria adopted, test conditions and so on.

Table 2-5 Summary of thermal comfort studies on temperature cycles

References	Sample size	Age group	Thermal conditions	Amplitude/frequency/ rate of temperature change	Mean radiant temperature	Duration	Voting scales	Implications on the range of comfort zone due to temperature variations
Sprague and McNall (1970)	192	College age	M= 1.2 met; I_{cl} =0.6 clo; T_r=25.6 °C; RH=45%; v < 0.15 m/s.	Peak-to-peak amplitudes 0.6°C–3.3°C; 1.7 °C/h–10.9 °C/h; 1.0–2.0 cycles/h	Constant at 25.6 °C through all the test conditions	3 h	Discrete/continuous 7 category thermal sensation scale	Decreased comfort zones with increased rate of change
Wyon et al. (1971)	8	19–25	T_r=28 °C, I_{cl} =0, RH=50%; T_r=25°C, I_{cl} =0.6 clo, RH=50%.	The amplitude is under subjects' control; 9°C/h, 30 °C/h	Fluctuation amplitude about 20% of air temperature amplitude at 30 °C/h and 30% at 9 °C/h	2 h mental work followed by 2 h rest	Spontaneous dial voting when the temperature was too hot or too cold	Increased comfort zones with increased rate of change
Wyon et al. (1973)	16	21–28	T_r=24.5 °C, M= 1.2 met; I_{cl} =0.6 clo; v < 0.1 m/s	Peak-to-peak amplitudes 2°C, 4°C,6°C,8°C; 15 °C/h, 30°C/h, 45°C/h, 60 °C/h; 1.9–7.5 cycles/h	Amplitudes were lower than half of the intended amplitudes	7 h 48 mins on successive days	A different version of dial voting method	The width of comfort vote distribution increases with higher amplitudes, but discomfort votes increase as well
Nevins et al. (1975)	18	19–55	T_r=25 °C; M = 1.2 met; I_{cl} = 0.6 clo; RH = 50%; v = 0.25 m/s	Peak-to-peak amplitudes of 10 °C; 18.7 °C/h on average; 0.9 cycles/h	About the same changing rate as air temperature	2 h	ASHRAE 7-point thermal sensation scale and 5 category comfort scale	Same comfort zone as in steady state conditions
Rohles et al. (1980)	804	18–23	M = 1.2 met; basal temperature 17.8 °C–29.4 °C; I_{cl} = 0.6 clo; RH = 50%;	Amplitudes 1.1°C–5.6 °C; 1.1–4.4 °C/h; 0.3–1.5 cycles/h	Not mentioned	Variant	9 category thermal sensation scale and 7 category semantic differential comfort scale	Same comfort zone as in steady state conditions

(M—Metabolic rate; I_{cl}—clo value; T_r—reference/control temperature; RH—relative humidity; v—air speed)

Among the above-mentioned variants, two factors are the most pronounced and influential: the mean radiant temperature and thus the resulting operative temperature; the voting scale and acceptability criteria adopted. Among the 5 experiments reviewed here, only Nevins' experiments have adopted fluctuating mean radiant temperature that has about the same changing rate as the air temperature; Sprague and McNall's experiment have kept the mean radiant temperature constant at the basal temperature of air fluctuation. In other experiments, Due to the heat capacity of the walls, floors, and ceilings, the mean radiant temperature will be delayed and damped during the air temperature fluctuation. According to ASHRAE 55 (2013), at an air velocity of 0.20 m/s or less, the operative temperature is the arithmetic mean of dry bulb temperature and mean radiant temperature, so the actual tolerated comfort zones in operative temperature were narrower than that have been reported by Sprague and McNall (1970), Wyon et al. (1971, 1973) and Rohles et al. (1980).

Hensen (1990) has converted the air temperature fluctuation amplitudes to the corresponding operative temperature amplitudes for above experiments and plotted them against tested frequency in his literature review. Figure 2-16 adapts his original graph by comparing the experimental results with ASHRAE 55 (2013) standard. It is obvious that the new ASHRAE 55 (2013) allows larger amplitudes and rate of temperature change for ramps, drifts and cycles with lower frequencies than the old version in 1981. Presumably, this revision may come (partly) from the experimental results.

The usual thermal acceptability scale is based on the 7-category ASHRAE thermal sensation scale from which thermal sensation votes beyond ±1 represent a dissatisfied person (ASHRAE 55, 2013). However, in the above experiments, variant semantic voting scales have been used (Table 2-5), which leads to different acceptability criteria. Unusual acceptability criteria may cause either an increased or a decreased comfort zone than predicted by the usual one.

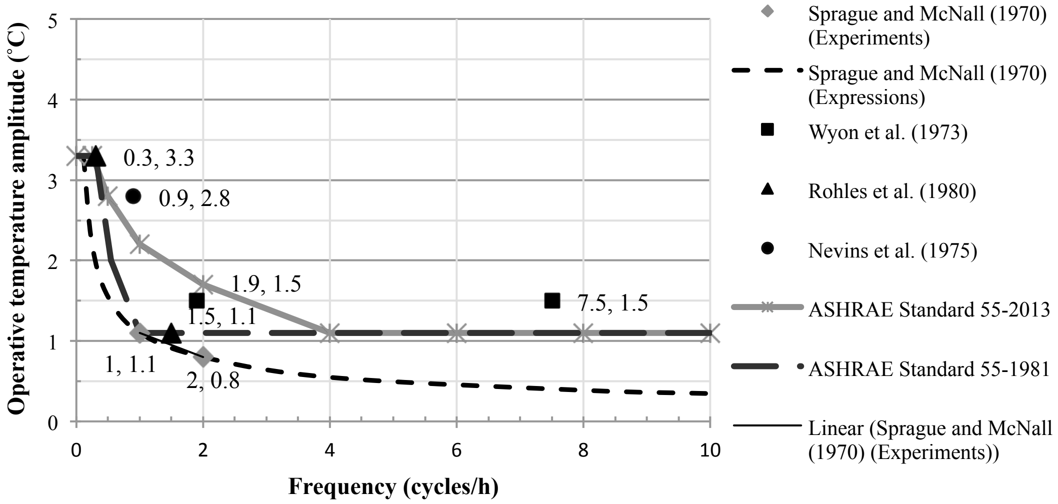


Figure 2-16 Maximum acceptable peak-to-peak amplitudes of cyclical fluctuating operative temperature as a function of cycle frequency for near-sedentary activity while wearing summer clothing (Adapted from Hensen, 1990)

Despite the differences and conflicts, Figure 2-16 indicates a trend that with cyclical fluctuating ambient temperatures the bandwidth of acceptable temperatures decreases with increasing fluctuation frequency. This bandwidth seems to be at its maximum in steady-state conditions. Figure 2-16 also suggests that there is a certain amplitude threshold (at about 1°C) below which the influence of fluctuation frequency is negligible.

Temperature ramps and drifts

Table 2-6 summarizes 6 climate chamber experiments on temperature ramps and one experiment on temperature drifts. It should be mentioned that theses experiments either have used chamber shells with air space inside, ensuring air temperature and mean radiant temperature are equal during the experiments, or have adopted well-insulated walls with a low thermal mass so that mean radiant temperature changes near instantly following air temperature fluctuation. Thus, the results of these experiments generally do not require amendments that are needed for above experimental results on temperature cycles. In the following, some important results of the experiments will be analysed and compared.

Table 2-6 Summary of thermal comfort studies on temperature ramps and drifts

References	Sample size	Age group	Thermal conditions	Amplitude/ range/ frequency/ rate of temperature change	Duration	Voting scales	Detectability of temperature change	Thermal sensitivity	Validity of PMV/PPD methods in predicting thermal comfort zone
Griffiths and McIntyre (1974)	32	16–19	T_r=23 °C; I_{cl} = 0.7–0.9 clo; v < 0.1 m/s; vapour pressure within 10 mb ±2·2 mb	±1.5 °C, ±3 °C, and ±4.5 °C from 23 °C; ±0.5 °C/h, ±1.0 °C/h, ±1.5 °C/h	6 h	Bedford Warmth Scale and 7 category subjective voting scale	Even lowest changing rate (±0.5°C/h) was detected by subjects when the ramp starts	No difference	Thermal comfort zone agrees well with predicted by PMV/PPD
Berglund and Gonzalez (1978a)	36	18–28	T_r=25 °C; M = 1.2 met; I_{cl} = 0.5, 0.7, 0.9 clo; v = 0.1 m/s; T_d=12 °C	±2 °C, ±4 °C, and ±6 °C from 25 °C; ±0.5 °C/h, ±1.0 °C/h, ±1.5 °C/h	4 h	ASHRAE thermal sensation scale and binary acceptability scale	Subjects cannot detect slow temperature change of ±0.5 °C/h; +1°C/h and +1.5°C/h ramps are detected with 1hr lag.	Higher during ±1.0 °C/h ramp than during ±1.5 °C/h ramp, but inconsistent with ±0.5 °C/h ramp	Thermal acceptability is wider than predicted by PMV/PPD for all ramps
Berglund and Gonzalez (1978b)	24	19–33	T_r=25 °C; I_{cl} = 0.32–0.72 clo; v = 0.1 m/s; T_d=10 °C, 20 °C	23 °C–27.8 °C; 0.6 °C/h	8.5 h	ASHRAE thermal sensation scale and binary acceptability scale	Subjects cannot detect temperature change for the first 2 hours	—	Thermal acceptability is wider than predicted by PMV/PPD
Rohles et. al. (1980)	84	18–22	I_{cl} = 0.8 clo	One-hour drift: 22.3 °C–27.8 °C, Half-hour drift: 22.3 °C–26.1 °C; Up to 4.44 °C/h for one-hour drift, 5 °C/h for half-hour drift	0.5–1 h	9 Category thermal sensation scale and 9 category thermal comfort ballot	Subjects can detect temperature changes for both drifts	—	Thermal comfort zone is slightly narrower than predicted by PMV/PPD
Knudsen et. al. (1989)	40	21–25	T_r=19.5 °C, 21.5 °C, 23.5 °C; M = 1.2 met; I_{cl} = 0.8 clo; RH = 50%; vapour pressure 1.28 kPa	±3 °C, ±7.5 °C from 21.5 °C; ±1 °C/h, ±5 °C/h	1.5–3 h	ASHRAE thermal sensation scale and 4 category acceptability scale	Subjects detect temperature changes for both ±1°C/h and ±5°C/h changing rate.	No difference	Thermal comfort zone is narrower for both ±1 °C/h and ±5 °C/h ramps in the cooler side than predicted by PMV/PPD model
Kolarik et. al. (2009)	52	19–28	T_r=24.4, 21.4 °C; M = 1.2 met; I_{cl} = 0.5, 0.7 clo; RH = 50%;	Experiment 1: 22 °C–26.8 °C; Experiment 2: 17.8 °C–25 °C; ±0.6 °C/h, ±1.2 °C/h, +2.4 °C/h, +4.8 °C/h	1–8 h	ASHRAE thermal sensation scale, 4 category acceptability scale	Very moderate ramps (±0.6 °C/h) are detected by sedentary subjects with 3–4 hours delay (depending on clothing value)	In Experiment 1, sensitivity is significantly higher in +0.6 °C/h ramp than in +1.2 °C/h, +2.4 °C/h, and +4.8 °C/h ramps; in Experiment 2, -0.6°C/h ramp has the highest sensitivity, then the -	Decreased comfort zone for 4.8 °C/h ramp; increased comfort zone for 0.6 °C/h in the warm side; same (similar) comfort zone for the other ramps

								1.2°C/h ramp; the +0.6 °C/h and +1.2 °C/h ramps have the lowest sensitivity.	
Schellen et. al. (2010)	16 (all men)	Young: 22–25; Old: 67–73	T_r=21.5 °C; M = 1.2 met; I_{cl} = 1.0; v = 0.19±0.03 m/s; RH = 40%	17°C–25°C; First 4 h: +2 °C/h; Last 4 h: –2 °C/h	8 h	ASHRAE thermal sensation scale and 4 category comfort scale	Subjects can detect temperature changes instantly	Generally the same for young and old subjects	TSV agrees well with PMV for young subjects, but is 0.5 unit lower for old subjects; slightly increased comfort zone

(M—Metabolic rate; I_{cl}—clo value; T_r—reference/control temperature; RH—relative humidity; v—air speed; T_d—dew point temperature)

In respect of subjects' detectability of temperature fluctuations, the experimental results seem to be rather consistent: when the operative temperature changing rate is as moderate as ±0.5 °C/h, subjects will not even notice the change; a slightly increasing changing rate of ±0.6 °C/h can be detected by subjects with 2–4 hours delay; larger changing rate (±1 °C/h or above) will be detected sooner or instantly. However, result from Griffiths and McIntyre (1974) was the only exception. They reported that even the lowest changing rate (±0.5 °C/h) was detected by subjects when the ramp started. Comparison of Griffiths and McIntyre (1974)'s and Berglund and Gonzalez (1978a)'s experimental parameters reveals that except the basal (initial) temperatures and fluctuation amplitudes, other parameters in the two experiments are rather similar. Consequently, the distinct results might indicate that these two factors were related to subjects' detectability of temperature ramps.

Thermal sensitivity is defined as ΔTSV/ΔT by Berglund and Gonzalez (1978a) where ΔTSV means change of thermal sensation vote on the ASHRAE 7-point scale and ΔT means change of operative temperature. The experiments demonstrate that thermal sensitivity is neither affected by clothing (Berglund and Gonzalez, 1978a) nor affected by age (Schellen et al., 2010). Regarding thermal sensitivity vs. rate of temperature change, the majority of experiments have not reported any direct relationship (Griffiths and McIntyre, 1974; Knudsen et al., 1989; Schellen et al., 2010). However, Kolarik et al. (2009) found that subjects (0.5 clo) had significant higher thermal sensitivity for the +0.6

°C/h ramp than for the +1.2 °C/h, +2.4 °C/h, and +4.8 °C/h ramps during temperature variations from 22 °C to 26.8 °C. However, during temperature range of 17.8 °C–25 °C, subjects' thermal sensitivity in the +0.6 °C/h ramp was not different from in the +1.2 °C/h ramp. Comparing the increasing ramps (+0.6 °C/h and +1.2 °C/h) with the decreasing ones (-0.6 °C/h and -1.2 °C/h), subjects were more sensitive to decreasing ones and they could also differentiate decreasing ramps with different rates of change (-0.6 °C/h and -1.2 °C/h ramps). The author inferred that it might not be the temperature ramp itself, but rather a combination of temperature level above the neutral temperature and duration of exposure that have influenced the thermal sensation of subjects (Kolarik et al. 2009). This explanation may seem reasonable, but it might not be used to explain the thermal sensitivity inconsistency in the experiments of Berglund and Gonzalez (1978a), where sensitivity during ±1.0 °C/h ramp is higher than during the ±0.5 °C/h and ±1.5 °C/h ramps with the only exception of during -0.5 °C/h (0.5 clo), since duration of exposure for all ramps are 4 hours, and the largest deviation from neutral temperature was during ±1.5 °C/h ramp. However, the authors did not provide with any explanation why thermal sensitivity during ±1.0 °C/h ramp was so high.

PMV Model was developed by Fanger (1972) to predict occupants' thermal sensation during steady states. In the experimental studies on temperature ramps and drifts, the adoption of ASHRAE 7-point thermal sensation scale by most of the experiments enabled the comparisons between thermal sensation vote (TSV) tested in respective experiments with predicted by PMV model. The results showed that generally, these two parameters were in reasonably good agreement for young subjects (Griffiths and McIntyre, 1974; Knudsen et al., 1989; Kolarik et al., 2009; Schellen et al., 2010). Knudsen (1989) concluded that PMV model might be possible to predict thermal sensation for a rate of temperature change up to ±5.0 °C/h.

As for thermal comfort zone width compared with steady states, contradictory results have also been reported: Berglund and Gonzalez (1978a and 1978b) and Schellen et al. (2010) reported increased comfort zone width (thermal acceptability) than in steady states; Griffith and McIntyre (1974) reported the same comfort zone width; Rohles et al. (1980) and Knudsen et al. (1989) reported decreased comfort zone while Kolarik et al. (2009) reported inconsistent results for different ramps. As mentioned before, discrepant thermal acceptability criteria are likely an important cause of the inconsistent findings; another factor might include human thermoregulation control mechanisms that will be discussed in the following.

In spite of the conflicts, the above experiments seem to imply that the thermal acceptability of subjects during ramps and drifts are related to the rate of temperature change that they are exposed to. As have been supported by most experiments and pointed out by Hensen (1990), moderate temperature changes up to 0.5 °C/h had no influence on the width of the comfort zone as established under steady-state conditions. For operative temperature changing rates between 0.5 °C/h and 1.5 °C/h, there was no clear evidence of increased or decreased comfort zones due to temperature drifts, except from experiments with uncommon acceptability assessment procedures. Hensen's review (1990) was before Knudsen, Schellen and Kolarik's studies. Excluding Berglund's experiments that employed uncommon acceptability criteria, Hensen's conclusion on this band of changing rate was most probably based on Griffiths and McIntyre (1974)'s experiments.

The recent studies by Knudsen et al. (1989) and Kolarik et al. (2009) have adopted the same thermal sensation scale and acceptability scale (ASHRAE thermal sensation scale and 4 category thermal acceptability scale), and similar operative temperature changing rates have been tested in both experiments. Consequently, it is possible to compare the thermal acceptability during 1.0 °C/h and 5.0 °C/h ramps (approximate) in both experiments. In Knudsen's studies, the thermal acceptability during both ±1.0 °C/h and ±5.0 °C/h ramps was lower than predicted by PPD model in the cooler side, but fit well with PPD model during ±5.0 °C/h ramp in the warmer side; thermal acceptability was higher for the whole range of thermal sensation during ±5.0 °C/h ramps than during ±1.0 °C/h ramps. Kolarik et al. (2009) also reported a decreased comfort zone during the 4.8 °C/h ramp, as the percentage of dissatisfied subjects increased faster than predicted by PPD model, however thermal acceptability during ±1.2 °C/h ramps fit well with predicted by PPD model, which did not agree with Knudsen's findings.

2.2.3. Dynamic thermal comfort and alliesthesia

The most common thermal sensation models are Fanger's PMV model (Fanger, 1972) and Gagge's 2-Node model (Gagge, 1970), both catering for uniform and steady state conditions. Dynamic thermal sensation models include a derivative that corresponds to sensations induced by changing (transient) conditions, which are correlated with the responses of the body's thermal receptors.

Ring and de Dear (1991) and de Dear et al. (1993) developed a skin receptor impulse frequency model based on humans' ability to instantaneously detect changes in the thermal environment from the cutaneous thermoreceptors. The cutaneous thermoreceptor includes both static and dynamic components: the static component being proportional to the temperature at the receptor site, and the dynamic component being proportional to rate of change with respect to time in local skin temperature. When exposed to a temperature up-step, warm receptors respond with a sudden spike in impulse frequencies, and then decay back to its static response. The cold receptor follows the similar pattern during a temperature down-step, except that the intensity of cold overshoot could be about twice the size of the corresponding warm overshoot derived from the same but opposite direction temperature transient, as have been observed by de Dear et al. (1993). This appears to result primarily from cold receptors being closer to the skin surface than warm receptors, and also from the higher sensitivity of cold receptors to skin temperature change. Fiala et al. (2003) proposed a dynamic thermal sensation model from physiological states using a multi-node, dynamic model of human thermoregulation for spatially uniform transient conditions. Zhang et al. (2010a, b, c) proposed a model that predicts both sensation and comfort at the local body parts level as well as the whole-body level to evaluate comfort in nonuniform and transient environments; this model cannot predict participants' subjective states (thermal responses) from objective environmental measurements.

Hensel (1981) concluded that faster thermal transients required smaller deviations of skin temperature from neutral to produce a just noticeable sensation than was the case for slower temperature transients, meaning that there is a threshold for thermal sensation and it is affected by the rate of temperature change. Evidence can be found to support this assertion from the experiments on temperature ramps and drifts that thermal sensation during very moderate temperature changing rate will not deviate from that in steady states whereas during higher rate of temperature change, thermal sensation closely follows temperature change; another evidence lies in the experiments on temperature cycles where subjects accept smaller amplitudes of temperature when the rate of temperature change is faster, as is demonstrated by Figure 2-16.

The threshold of thermal sensation is also determined by the adapting temperature (the temperature to which the skin is adapted when the change starts), the direction of temperature change, the exposed part of the body and the area being exposed. Thus, different basal temperatures, different clothing ensembles, and global or local cooling/heating methods used in the above experiments may partly contribute to the conflicting results in Table 2-5 and Table 2-6 as well. As have been pointed out by Hensen (1990), thermoregulation systems during transient conditions are highly complex, and the knowledge about the processes involved is too limited to control all relevant parameters during experiments. Yet, the model of heat diffusion in cutaneous tissue put forward by Ring and de Dear (1991) have provided a good basis to predict thermal sensation in transient conditions, and the model was successfully extended to ambient temperature transients and clothed skin conditions (de Dear et al., 1993).

The term alliesthesia was coined by Cabanac (1971) for homeostatic systems in which a given stimulus can induce either a pleasant or an unpleasant experience, depending on the subject's internal state. De Dear (2011) has summarized the concept of alliesthesia as "any external or environmental stimulus that has the prospect of restoring the regulated variable within the milieu interieur to its setpoint will be perceived as pleasant (positive alliesthesia), while any environmental stimulus that will enlarge the error between the regulated variable and its setpoint will be perceived as distinctly unpleasant, or even noxious in more extreme cases (negative alliesthesia)". Parkinson and de Dear (2014) further developed the concept of spatial alliesthesia, referring to the perceptual process derived from rapid changes in local skin temperature driven predominantly by cutaneous thermoreceptors instead of the more conventional whole-body model of alliesthesia driven by load errors of central origin (Cabanac, 1971; de Dear, 2011).

2.2.4. General conclusions

This review summarizes and compares 2 current international standards regarding thermal comfort during transient conditions and 12 climate chamber studies on temperature cycles, ramps and drifts, the results of which were further related to thermoregulation theories during temperature transients. General conclusions can be obtained from above analysis as follows:

- ISO 7730 (2005) standard is more conservative in defining the limitations on rapid temperature variations than ASHRAE 55 (2013).
- Climate chamber studies on temperature cycles, ramps and drifts have yielded contradictory results due to variant experimental parameters between different experiments, which include the mean radiant temperatures, voting scales and acceptability criteria, operative temperature changing rates, amplitudes of fluctuation, adapting (basal) temperatures, clothing ensembles, and global or local cooling/heating methods, etc.
- For temperature cycles, the experiments show a trend that the bandwidth of acceptable temperatures decreases with increasing fluctuation frequency. This bandwidth is at its maximum in steady-state conditions. There is a certain amplitude threshold (at about 1°C) below which the influence of fluctuation frequency is negligible.

- For temperature ramps and drifts, the experiments consistently showed that subjects' thermal sensitivity was neither affected by clothing nor age. Regarding thermal sensitivity vs. rate of temperature change, no consistent relationship can be observed in these studies. Moderate operative temperature changing rate of lower than 0.5 °C/h has no influence on thermal sensation or thermal comfort (acceptability) than in steady states. TSV and PMV generally are in reasonably good agreement for young subjects and Knudsen et al. (1989) concluded that the PMV model might be possible to predict thermal sensation for a rate of temperature change up to ±5.0 °C/h. As for thermal comfort zone width compared with steady states, contradictory results have been reported.
- Thermoregulation and thermoreceptor theories can qualitatively resolve (in part) the conflicts of the experimental results. However, the quantitative relationship is mostly beyond the scope of current knowledge.

2.3. HUMAN MENTAL PERFORMANCE IN VARIANT THERMAL ENVIRONMENTS

2.3.1. Mental performance under static environments

There is a substantial body of literature addressing thermal environmental effects on human performance[4] under static thermal environments. 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 mental 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

[4] Mental performance, cognitive performance and productivity have been used interchangeably in this study.

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; Lovingood et al., 1967; Colquhoun and Goldman, 1972). Hancock and Vasmatzidis (2003) mentioned 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), meaning that there was only one single optimum temperature or TSV value corresponding to the maximum mental performance. 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 and Fisk (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 and Fisk (2006) clearly presented an inverted-U relationship with performance peaking at 21.6 °C (Figure 2-17, left): "performance increases with a temperature up to 20 °C–23 °C and that performance decreases with a temperature above 23 °C–24 °C. The slope equals zero at a temperature of 21.6 °C." "We further developed a curve of performance in relation to maximum performance. For example, at a temperature of 30 °C the performance is 90% of the maximum performance at 21.6 °C, i.e., a reduction in performance of 10%." The above quoted texts clearly assert that there was a single optimal temperature, which was 21.6 °C corresponding to the maximum performance.

What's more, this ambiguity is further reflected in ASHRAE Handbook—Fundamentals (2013), which is an official guideline for HVAC engineers. In the text of ASHRAE Handbook—Fundamentals (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 Handbook—Fundamentals (2013) contradicts this statement. In Figure 2-17 (right), it is obvious that the relative performance follows an inverted-U relationship with temperatures: the optimal comfort temperature, as defined by T_c in Figure 2-17 (right), leads to the 100% relative performance and any deviation from this optimal temperature causes a decrement of performance. Although the text stated, "the results show that performance decreases as temperature deviates above or below a thermal comfort temperature range", there is no indication or definition of this so-called "temperature range" in the figure.

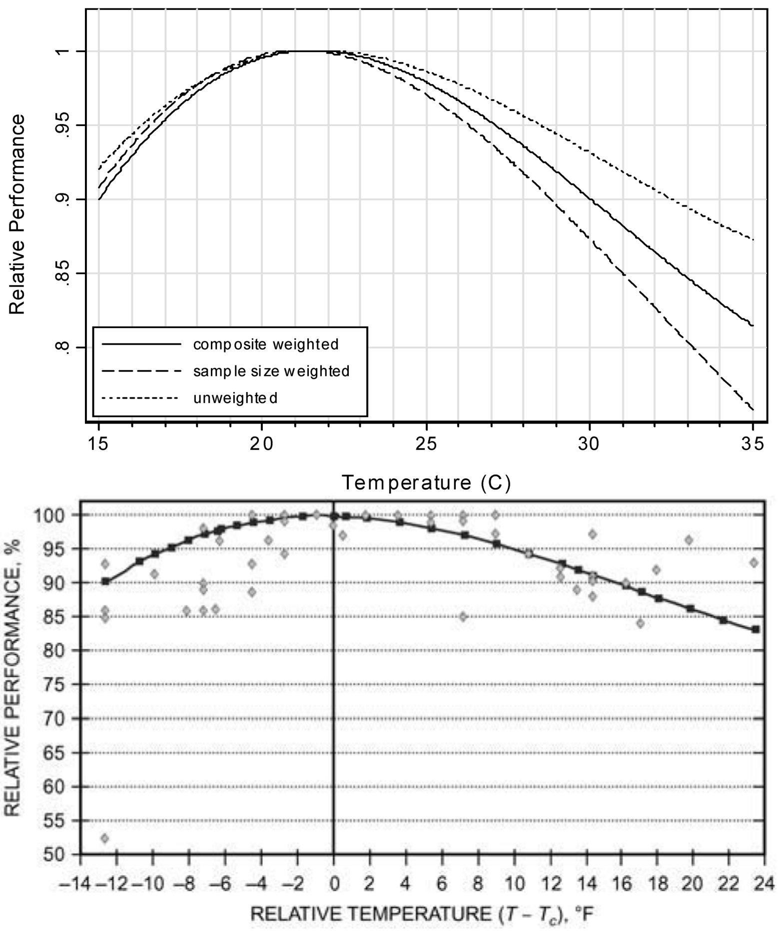


Figure 2-17 Relative performance vs. temperature derived from Seppänen & Fisk (2006) (left) and ASHRAE Handbook—Fundamentals (2013) (right)

2.3.2. Mental performance under transient conditions

Most of the human mental performance studies have been conducted in static thermal conditions while only a few studies have examined the performance under transient thermal environments.

Temperature Cycles and Performance

Studies by Wyon et al. (1971, 1973) are the only studies found concerning the impacts of temperature cycles on subjects' mental performance and productivity.

Wyon et al. (1971) investigated the factors affecting subjective tolerance of temperature swings. Spontaneous dial voting was adopted so whenever the temperature was too hot or too cold, subjects were able to reverse the direction of temperature change.

The authors found that subjects tolerated greater amplitudes when performing mental work than when resting.

In another study, Wyon et al. (1973) investigated the effects of pre-determined temperature swings on comfort and performance under normal working conditions. The authors hypothesized that a constant temperature would create a monotonous climate, thus increase fatigue, and decrease arousal and task performance. Sixteen participants with standard uniform (0.6 clo) were exposed to temperature cycles around a mean value of 24.5 °C at rates of 0.25, 0.5, 0.75 and 1.0 °C/min and peak-to-peak amplitudes of 2, 4, 6, and 8 °C over two 4-hour periods. The authors found that small rapid swings around the preferred temperature resulted in a 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. It was concluded that large temperature swings may have a positive effect on performance, but they increased discomfort as well thus should be self-imposed; small rapid temperature swings were equivalent to a small increase in temperature.

Temperature Ramps, Drifts and Performance

Previous laboratory studies regarding effects of temperature ramps on subjects' mental performance haven't yielded any consistent significant positive or negative results (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 was 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: tasks such as anagram solving, time to rate resumes, vigilance task and distraction from temperature changes were negatively affected by ramping, whereas satisfaction of performance, time to rate magazines, motivation and short-term memory were improved by ramping.

Kolarik et al. (2009) conducted two related laboratory experiments on operative temperature ramps with different slopes, directions and durations. The first experiment covered a temperature range of 22 °C–26.8 °C and subjects wore light clothing (0.5 clo). Four temperature ramps (0.6 °C/h, 1.2 °C/h, 2.4 °C/h, and 4.8 °C/h) as well as a constant neutral temperature condition at 24.4 ºC were examined. The second experiment had a temperature variation between 17.8 °C and 25 ºC with subjects wearing heavier clothes (0.7 clo). Temperature ramps of 0.6 °C/h, 1.2 °C/h, -0.6 °C/h, and -1.2 °C/h and exposure to a constant temperature of 21.4 °C were examined. Subjects' performance was measured by simulated office work, including tasks such as addition, proofreading, reading and comprehension, and text typing. 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 two different conditions: the first is a control condition in which the temperature was constant at 21.5 °C; the second was a moderate temperature ramp (temperature range 17-25 °C, first 4 h: +2 °C/h, last 4 h: -2 °C/h). Productivity and performance were assessed with a "remote performance measurement" (RPM) method (Toftum et al., 2005), using two simulated office tasks: text typing and addition. The results indicated no effect of the temperature change on the performance of the subjects.

2.3.3. General conclusions

The effects of heat stress on human cognitive performance have been extensively studied. Yet, contradictory results have been reported that are likely resulted from differences in task complexity, skill levels of subjects, duration of exposure and so on. Many investigators in the indoor environmental quality field have examined the impacts of moderate thermal environments on occupants' mental performance, and confirmed an inverted-U relationship, meaning that there was only one single optimum temperature or TSV value corresponding to the maximum mental performance.

Human mental performance under thermal transients is not adequately studied. Laboratory experiments in mental performance during temperature cycles, ramps and drifts generally did not yield any consistent significant positive or negative results.

2.4. Thermal Comfort and Learning Performance in School Buildings

The primary purposes of school buildings are to provide healthy, productive and comfort places for students to achieve their optimum learning performance. Consequently, school buildings are complex and demanding to design, as they need to perform well in all aspects of indoor environmental conditions; meanwhile they need to accommodate periods with very high occupant densities. The typical classroom has on average four times as many occupants per square metre as the typical office building (Chatzidiakou et al., 2012).

The majority of studies on thermal comfort in school buildings focus on tropical settings (kWok & Chun, 2003; Wong & Khoo, 2003; Hwang et al., 2006; Liang et al., 2012), with only a few studies conducted in mild (Corgnati et al., 2007; Mumovic et al., 2009) or cold climates (Mors et al., 2011). Overall the findings indicate that satisfaction of the occupants with thermal conditions depended on local climate, season (Corgnati et al., 2009) and ventilation system, as occupants in naturally ventilated classrooms accepted a wider range of temperatures compared with mechanical settings (kWok & Chun, 2003; Wong & Khoo, 2003).

Current evidence on the association between thermal conditions and cognitive performance of students is very *limited*. In two representative field studies with primary school students, Wargocki & Wyon (2013) and Bakó-Biró et al. (2012) both focused on slightly warm/ warm thermal sensations and adopted cross-sectional blind interventions. Wargocki & Wyon (2013) aimed to examine empirical dose-response relationship between the performance of schoolwork and classroom temperature, and suggested that for every 1 °C reduction academic performance in terms of speed was improved by 2% to

4%. Bakó-Biró et al. (2012) reported similar findings from investigations in English primary schools. The analysis of cognitive performance of pupils suggested an improvement by about 6% to 8% when lowering the temperature from 25.3 °C to 23.1 °C. Chatzidiakou et al. (2014) developed a linear regression model to combine evidence extracted from the two studies (Figure 2-18). Overall, the synthesised relationship showed that an improvement of 11.0% (95% CI: 10.0%–11.2%) in cognitive performance may be expected when temperature drops from 25 °C to 20 °C. Another study (Mi et al., 2006) found a suggestive relationship that temperatures at the lower end of the comfortable range may improve health, cognitive performance and perception of school children.

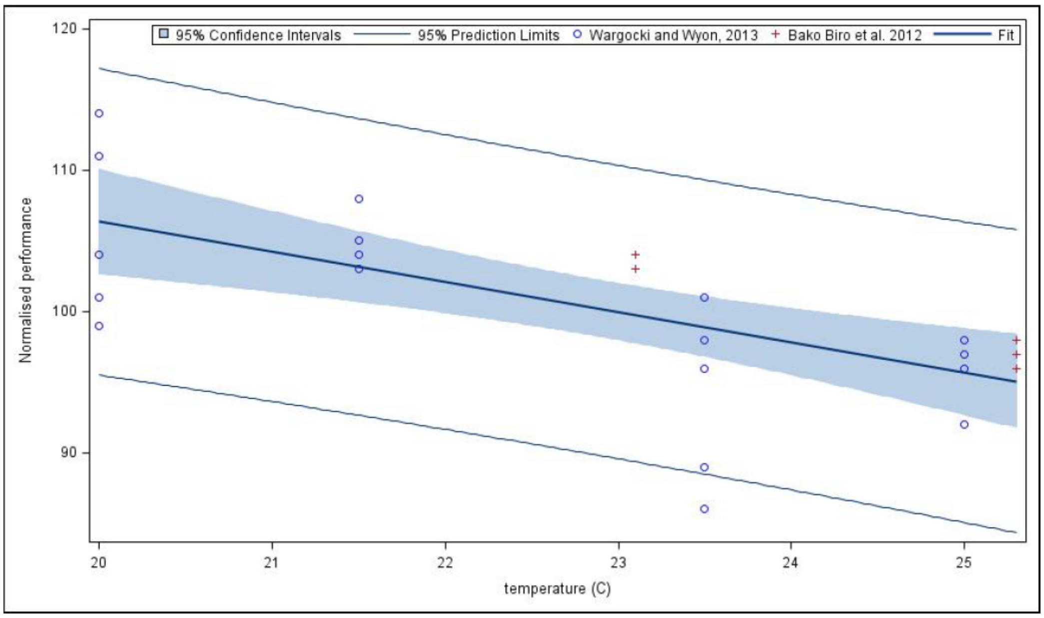


Figure 2-18 Normalised performance as a function of classroom temperature (Chatzidiakou et al., 2014).

There were no experiments in school settings that investigate cognitive performance of students in temperatures above 25 °C or below 20 °C in the previous literature.

2.5. Gaps to be Filled

As discussed in Section 2.1, many utility companies in USA and Australia have conducted trials on DLC AC duty cycle restriction in residential and small business buildings in recent years. Generally speaking, these programs have reported positive results in reducing peak demands without prompting excessive complaints from customers. However, to replicate the success of DLC in university lecture theatres, two factors must be taken into consideration before any realistic assessments can be made.

- Thermal comfort: considering the much higher occupant density in classrooms than in homes and office buildings, will the DLC-induced thermal environments be acceptable to students?

A lecture theatre has much higher occupant density (internal loads) than in a residence or a typical office building, thus requires much higher ventilation rates. Classrooms commonly have approximately 15 times greater ventilation volumes (outdoor airflow rate per floor area) than residences (Cummings and Withers, accessed 03-01-2016). The hot and frequently humid outdoor air that triggered the peak demand event in the first place will be continually introduced into the lecture theatre even when the AC compressor is cycled off, which may compromise occupants' thermal comfort during DLC events.

- Cognitive performance: will the DLC-induced thermal environments have any negative influences on students' learning performance?

Many previous studies have reported an inverted-U relationship between moderate thermal environments and occupants' mental performance, meaning that there is a single optimum temperature or TSV value corresponding to the optimum mental performance. Previous literature in students' cognitive performance in classrooms, though very scarce, suggested that lower temperatures in the comfort range might improve students' performance. Does it mean that the DLC-induced temperature cycles will inevitably jeopardize students' learning performance—the top priority over-and-above energy saving in lecture theatres?

Summarizing the previous literature on DLC studies, thermal comfort studies and mental performance studies, the following gaps can be identified.

- Previous DLC programs (studies) have been focused on residential buildings and small business buildings. There have been no DLC studies in university lecture theatre settings where there are two key determinants of acceptance of DLC—thermal comfort and cognitive performance;
- Previous DLC studies have not included a "point-in-time" thermal comfort survey which enables correlation between subjects' thermal comfort and thermal environmental parameters;
- Previous laboratory studies on thermal comfort during temperature cycles, ramps and drifts have yielded contradictory results on subjects' thermal sensitivity and thermal comfort zones during transient conditions;
- Previous literature about the effects of thermal transients on mental performance did not yield consistent results; literature in students' cognitive performance in classrooms was very scarce and only covered a very narrow temperature range.
- To date there has been no research study focusing on the thermal comfort or cognitive performance impacts of temperature cycles induced by direct load control strategies of peak electricity demand management.

2.6. RESEARCH QUESTIONS

The fundamental research question in this study is "what are the impacts, if any, of implementing direct load control strategies of peak electricity demand management on university students' thermal comfort and cognitive performance in lecture theatres during summer?" This research question can be sub-divided into questions related to thermal environments, human subjects' thermal comfort and cognitive performance.

- Thermal environment during DLC events
    1. What are the thermal environments during a DLC event using duty cycle restriction approach?
    2. Are there any differences in thermal environments in terms of variant off cycle fractions, cycling periods, adapting temperatures, building envelope

thermal performance levels and ventilation rates? If any, which factors have larger impacts?

3. Which DLC algorithms (off cycle fractions, cycling periods and adapting temperatures) can provide the optimized thermal environments under variant building envelope thermal performance conditions and ventilation rates?

- Thermal comfort
  1. What are subjects' thermal comfort responses to variant DLC air-conditioning events?
  2. What are the main environmental and demographic factors that affect subjects' thermal comfort? How do these factors interact with each other?
  3. How does thermal sensitivity vary between DLC air-conditioning events of different frequency and amplitude? How do acceptability results from this study compare with the ASHRAE 55 (2013) limits on temperature cycles, ramps and drifts?
  4. Can the steady-state PMV/PPD model (Fanger, 1972; ISO 7730, 2005) reasonably predict thermal sensation and thermal acceptability during DLC air-conditioning events? How does the thermal comfort zone change compared with steady states?
- Cognitive performance
  1. How do 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?
  2. What are the relationships between cognitive performance and commonly used thermal comfort indexes?
  3. What is the implication of these relationships on the controversy surrounding thermal environmental effects on productivity?

3. Methods

This chapter discusses in detail the methods adopted in this study, including computer simulation and laboratory experiments with human subjects. First, a full-factorial parametric simulation study is conducted to simulate various DLC-induced thermal environments within a typical university lecture theatre in Australia. Then, by applying the approaches to design of experiments (DOE), specifically the *orthogonal array* method, partial DLC simulation cases were selected for human subject experiments. During these exposures, thermal comfort surveys and cognitive performance tests were administered to a sample of subjects. Multilevel linear modelling was adopted to analyse the experimental data.

3.1. Methods Employed in This Study

There are generally two fundamental methodological approaches for Indoor Environment Quality (IEQ) research: field studies and experimental studies. Field studies provide information that is directly transferrable to the broader population in similar settings, but the analysis is restricted to statistical descriptions rather than mathematic relationships since exposure conditions cannot be manipulated or controlled. Experimental studies provide researchers with total control and allow more finely targeted research designs than field study methods. Nonetheless, the external validity of generalizing findings from laboratory experiments to the “real world” is less than in field studies.

Computer simulation is also a commonly used approach in the built environment research. By modelling real-life or hypothetical situations, computer simulation serves as an effective way to virtually investigate and predict the behaviour or performance of an object (system) under study before/ without it actually being engaged. By changing variables in the simulation, it is also possible to find the optimized performance.

In this research study, modes of inquiry include both computer simulation of DLC-induced thermal environments and laboratory experiments with human subjects under these simulated DLC events. The purpose of simulation is to *define* the environmental conditions during various DLC events, and these conditions are then used to *drive* the climate chamber for human subject experiments.

Simulations were used to set up building and HVAC systems in order to characterize thermal environments of a typical university lecture theatre induced by DLC events composed of various algorithms. The laboratory method was employed to test human subjects' thermal comfort and cognitive performance under simulated DLC events in a controlled climate chamber to examine the impacts of these DLC events. The overall methods employed in this study can be illustrated in Figure 3-1. Detailed methods and procedures are discussed as follows.

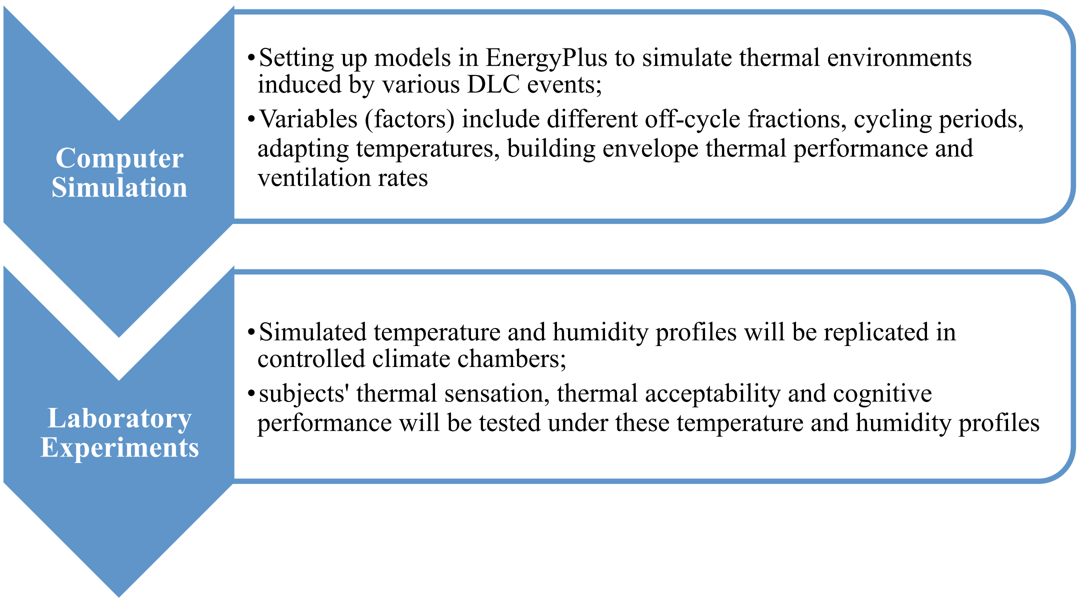


Figure 3-1 Interconnected research methods in this research design

3.2. Computer Simulation

As is discussed in Section 2.2, cycling the AC compressor on and off induces temperature cycles in the occupied zone, and the temperature fluctuation amplitude, periods and rate of temperature change depend on many factors including off cycle fraction (the amount of time the AC compressor is off during an activation period), cycling period (time for a complete cycle), cooling setpoint temperature, building envelope thermal performance, ventilation rate, and so on. By setting up a building and HVAC system model within building thermal simulation software environment, thermal environmental conditions resulting from a DLC event can be predicted.

Peak load reduction and maintenance of occupant comfort are two important goals for DLC programs, and DLC scenarios should be evaluated from both perspectives. However, at the level of a single building or customer, the peak load reduction is often not readily discernible due to the “rebound effect” (Zhang et al, 2013; Borlase, 2012) that refers to the even higher peak load often occurring immediately after the load shedding period. But at a macro level (utility companies or the aggregators), a large number of participating customers with staggered DLC events for sub-groups of customers can still achieve substantial peak load reduction over and above the rebound of sub-groups. This study does not address demand saving aspects of DLC scenarios, but rather focuses on the thermal comfort and cognitive performance impacts on occupants at the single-building scale. It presents results of simulated thermal environments within a typical university lecture theatre during DLC events, as induced by various off cycle fractions, cycling periods, cooling setpoint temperatures, building envelope thermal performance and ventilation rates.

DesignBuilder (Version 3.2, released in May 2013), and EnergyPlus (Version 8.0.0.008, released in April 2013), were used in this simulation study. DesignBuilder was used to set up the building geometry and HVAC system configuration. Since DesignBuilder does not allow sub-hour time-steps that are essential to HVAC cycling simulation in this study, EnergyPlus was then used to set up DLC control schemes and implement the simulation.

3.2.1. Test building and system description

Building

The building under study is located in a university campus in humid sub-tropical Sydney, Australia. This two-level building has a total floor area of 2,230 m^2, comprising four lecture theatres, one tutorial room, one canteen, two offices and some other auxiliary spaces. Figure 3-2 illustrates the simplified Level 2 plan of the test building. The eastern and western entrances on Level 2 are the main entrances to the building. All four lecture theatres have identical dimensions: 18.8 m length × 15.7 m width × 8.4 m height. They can be accessed either from the back doors located on Level 2 or the front doors located on Level 1 foyer. Lecture Theatre 1 and 2 have gone through minor repairs in 1993. Original timber benches have been replaced with individual theatre seats; all of the floor areas have been laid with carpets; the numbers of fluoresent lights have also been reduced.

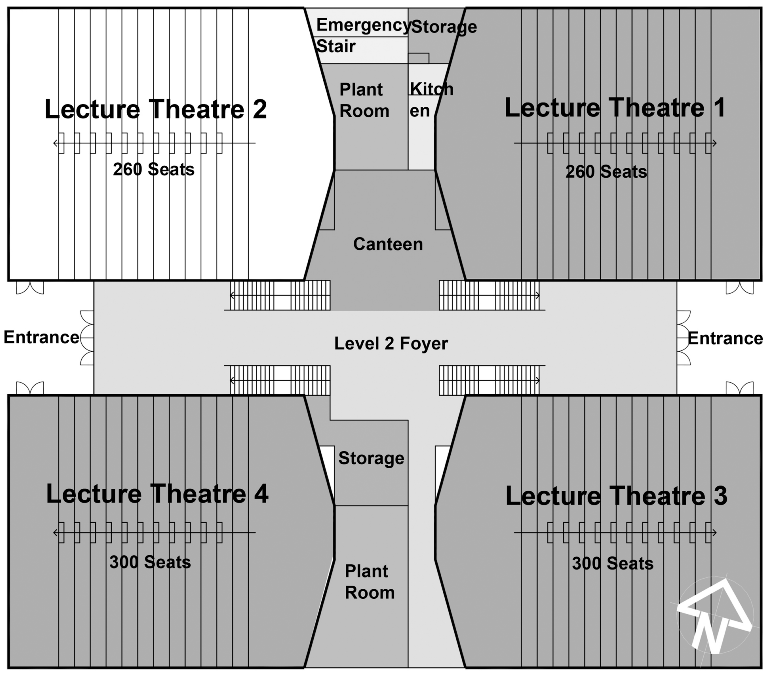


Figure 3-2 Simplified Level 2 plan of the test building

The external wall of the building is single skin brickWork supported by timber studwork construction similar to brick veneer. The internal wall is either double brick or single brick wall. There is no insulation in either the exterial walls or the roof structures. There are no external windows in this building except glass gliding doors on both Level 2 entrances and the pyramid roof skylight at the centre of Level 2 foyer. The building is normally open from 7 am to 6 pm on weekdays during teaching semester time, though it can be extended to 9 pm, or Saturdays, depending on lecture theatre bookings by academics. During non-semester time, lecture theatres are closed but the building's common areas remain open from 8 am to 4 pm.

HVAC Systems

The building was built in 1970 with a 200 kW natural gas boiler heating system serving four lecture theatres and the common foyer areas. The chilled-water system was installed around 1980. Chilled water is supplied at 6 ºC by a packaged reciprocating chiller set and a chilled water pump, to four conditioners located in level 2 plant rooms. Each conditioner, comprising two cooling coils, has a cooling capacity of 123 kW and serves a single lecture theatre. Condenser water is supplied at 29 ºC to the chiller from a forced draught cooling tower via a condenser water pump. The chiller has a cooling capacity of 301 kW and COP of 3.9. It was selected based on a design where two theatres are occupied simultaneously. Chilled water cooling coils operating between 6/13 ºC provide all cooling throughout the building. The design air flow rate for each lecture theatre is 4.7 m^3/s and the cooling supply air temperature is 13 ºC. The control system activates either chiller or boiler, depending on a central timer and thermostat. The cooling setpoint temperature is 22 ºC and the heating setpoint is 20 ºC. Capacity control for cooling and heating output is implemented by varying the chilled- or hot-water flow rate using 3-way modulating control valves while fixed fan speed delivers a constant air flow rate. The system does not have outside air economizers; there is no humidity control in this building as well. The tutorial room and the canteen each have their own Direct Expansion (DX) split system. Both Level 1 and Level 2 entry doors are kept open through the building opening hours so that the common foyers are naturally ventilated.

Simulation Model

The rendered geometry outline of the test building generated in DesignBuilder is shown in Figure 3-3. Investigations have been carried out in the test building to obtain actual internal load information, especially the occupancy schedule for model validation purposes. Though only two theatres were designed to be occupied simultaneously, it was observed that four theatres could hold students at the same time; however the normal occupancy for each theatre was only 60–140 students. Table 2-1 lists internal load inputs for main spaces in the test building.

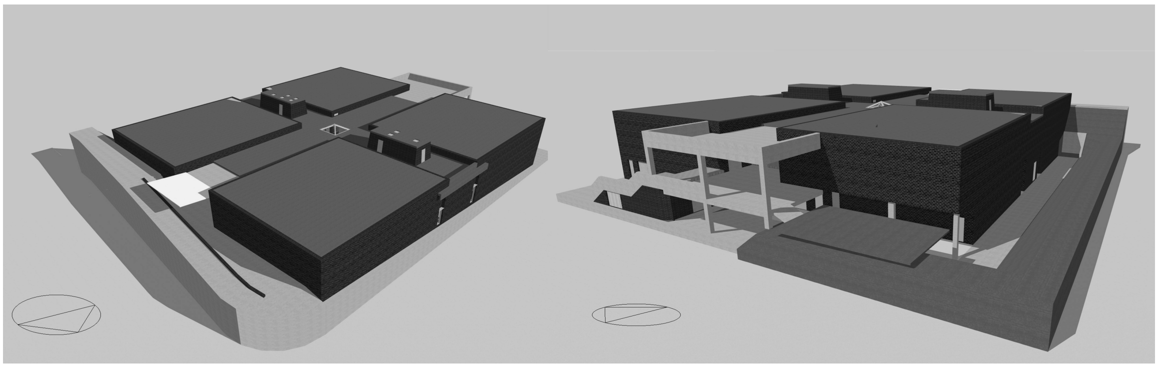


Figure 3-3 DesignBuilder model of the test building

Table 3-1 Internal loads for major spaces in the test building

Spaces	Area (m^2)	Conditioned	Maximum occupancy (people /m^2)	Maximum lighting density (W/m^2)	Equipment (W/m^2)
Lecture Theaters	288×4	Yes, Central AC	1.04 for Theatre 3/4; 0.9 for Theatre 1/2	6.9–13.4	2.1
Tutorial Rooms	56	Yes, Packaged DX	0.63	8.6	2
Foyers	396	No, naturally ventilated	0.05	10.2	8.5
Precinct offices	58	No	0.03	7.8	3
Canteen	55	Yes, Packaged DX	0.21	8.2	15
Kitchen	7	No	0.09	8	25
Toilets	99	No	0.11	5	5.6
Plant Rooms	62	No	0	5	50
Substation, Switch Room	97	No	0	5	30
Penthouses	40	No	0	2	40
Plinth Rooms	35	No	0	0	30

The "as built" building fabrics for external walls and roofs can be seen in Table 3-2 as defined by "poor building envelope thermal performance". For HVAC system models, the compound components of fans, cooling coils, heating coils and outdoor air mixers were represented by a four-pipe fan-coil unit in each lecture theatre within DesignBuilder. The DX systems in the tutorial room and canteen were represented by packaged terminal heat pumps with electric heating coils scheduled "off" at all times. The infiltration rate for the whole building was set to 1 ac/h based on the verification methods of building performance requirements in *Section J—Energy Efficiency* in National Construction Code Series Volume One (2013). The ventilation control mode in Level 1 and Level 2 Foyer was set to "constant" natural ventilation through the building opening schedule.

Weather Data for Simulation

The Sydney test building falls within Climate Zone 5 in Australia—a warm and temperate climate (National Construction Code Series, 2013). Although hourly based TMY2 or WYEC2 weather files from EnergyPlus were available, a nearby automatic weather station (Macquarie University Automatic Weather Station[5], accessed 20-03-2016) provides 15 min interval real-time weather data, offering a finer resolution than the interpolated hourly EnergyPlus weather data. Therefore, a "real day" was selected as the typical DLC event day. In preparing the EnergyPlus weather (EPW) file, actual observations of dry bulb temperature, dew point temperature, relative humidity, atmospheric pressure, global horizontal short-wave radiation, diffuse horizontal short-wave radiation, infrared sky radiation, wind speed and wind direction were obtained from the nearby weather station. Direct normal-to-beam radiation was calculated using the following algorithms (Auxiliary EnergyPlus programs, 2013):

$$Direct_{normal\ radiation} = \frac{Direct_{horizontal\ radiation}}{\sin(Solar_{height})} \qquad \text{Equation 3-1}$$

[5] http://aws.mq.edu.au/15min.php.

and

$$Direct_{horizontal\ radiation} = Global_{horizontal\ radiation} - Diffuse_{horizontal\ radiation}$$

Equation 3-2

For simulation of DLC events, a five-day 15min interval EPW file was compiled, containing the DLC event day and four preceding days. A 10min interval EPW file was also interpolated from the 15min one to match the needs of different cycling schemes and number of time steps in an hour for the simulation (Auxiliary EnergyPlus programs, 2013). The selected DLC event day was 22nd March, 2013 based on two considerations: first, investigations in universities' facility management departments in Sydney indicated that the highest electricity peak demand across the whole year typically occurs in March; second, the outdoor dry bulb temperature for a real DLC event is generally above 30 ºC. Figure 3-4 shows the weather profile on this selected DLC event day.

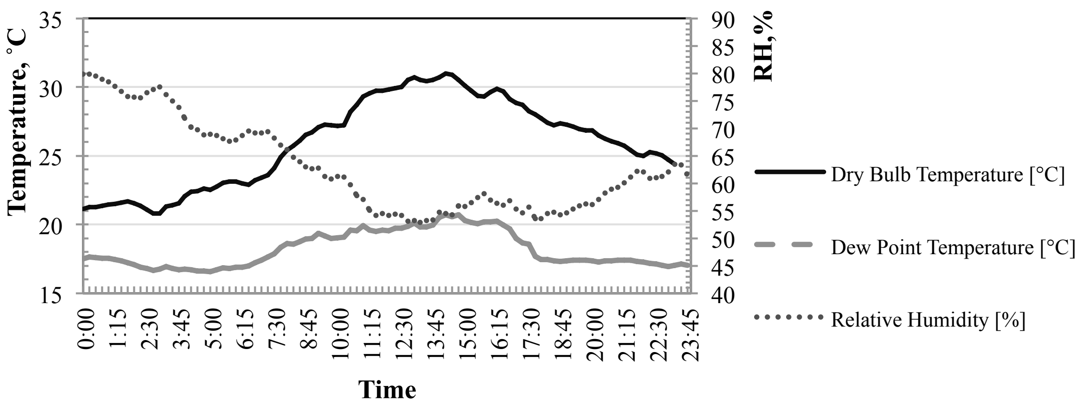


Figure 3-4 Dry bulb temperature, dew point temperature and relative humidity on the DLC event day

3.2.2. Model validation

The "as built" simulation model was validated using available electricity meter readings in two separate periods—July to October, 2012, and March to June, 2013. Real-time weather data (Macquarie University Automatic Weather Station, accessed 20-03-2016) for these two periods were used for validation. Occupancy schedules for the two validation periods were based on theatre booking information and direct observation. In

July to October, 2012, the actual consumption was 128.8 MWh compared to 137.3 MWh for simulation, giving an acceptable error of 6.6% according to ASHARE Guideline 14 (2002); in March to June, 2013, the actual consumption was 119.8 MWh and 110.5 MWh for simulation (error 7.7%). The simulated cooling energy consumption for each period was 25.4 MWh and 30.5 MWh respectively, which takes up 18.5% and 27.6% of the total energy consumption.

3.2.3. The simulation research design

Five factors have been identified to have direct influences on indoor thermal environments during DLC events. Other factors such as different HVAC systems and control modes will also have impacts, but are tangential to the research focus of this study. The five parameters and their different levels in the simulation research design are discussed below.

Off cycle fraction and cycling period

According to previous DLC trials and programs discussed in Section 2.1, 50% off cycle fraction and 0.5 hour cycling period are the most commonly used cycling schemes. Other off cycle fractions, such as 25%, 30%, 33%, 65%, 75%, 100% and different cycling periods, such as 1 hour have also been used. In this study, three off cycle fractions—33%, 50% and 67%, and two cycling periods—0.5 hour and 1 hour were selected for simulation.

Cooling setpoint temperatures preceding DLC events

Two levels of cooling setpoint temperatures were tested, 22 °C and 24 °C. The setpoint temperature of 22 °C was based on the actual cooling setpoint temperature observed in the Sydney test building, whereas 24 °C was derived from PMV by solving the model for zero, assuming that subjects' clo value is 0.5, activity level 1.2 Met, relative humidity 65%, air velocity 0.1 m/s, ambient temperature equalling to the radiant temperature, all of which representing typical parameters for sedentary occupants dressed in typical student summer clothing in Sydney.

Building envelope thermal performance

The thermal properties and performance of a building envelope can commonly be represented by two parameters: the overall heat transfer coefficient (U-Value) and the thermal capacity (thermal mass). U-Value measures the ability of the building envelope to conduct heat, thus a low U-Value usually indicates high level of insulation. Thermal capacity measures the ability to store heat. The building envelope with a high thermal capacity is effective in damping outdoor temperature fluctuations and maintaining relatively constant indoor temperature. Australian university buildings commonly adopt medium to heavyweight constructions with relatively high thermal capacity, such as concrete, bricks, etc. However, the insulation conditions of these buildings can vary significantly according to the years of construction. For this simulation, two levels of building envelope thermal performance typical for Australia's university building stock were selected. One is the original test building fabric for external walls and roofs, representing the uninsulated 1970's building with relatively high thermal capacity; the other selected from the "Best practice wall, heavyweight" and "Best practice flat roof (no ceiling), heavyweight" in the DesignBuilder building construction database, representing a well-insulated new building with high thermal capacity. Detailed building fabric layers and corresponding U-Values and solar absorptance values are listed in Table 3-2. Thermal properties of the main materials used in the simulation are listed in Table 3-3. Internal building specifications remain in the "as built" condition across all of the project's simulation scenarios.

Table 3-2 Two levels of building envelope fabric with U-Value and solar absorptance for the test building

Two levels of building envelope thermal performance	Building envelope					
	External walls			Roofs		
	Layers	U-Value ($W/m^2 \cdot K$)	Solar Absorptance	Layers	U-Value ($W/m^2 \cdot K$)	Solar Absorptance
Poor building envelope thermal performance	110 mm brick, 100 mm timber stud+ 260 mm air space non reflective and unventilated, 10	1.91	0.6	10 mm PVC, 40 mm floor/roof screed, 130 mm concrete reinforced	2.52	0.7

	mm gypsum plasterboard					
Good building envelope thermal performance	105 mm brick, 118 mm XPS extruded polystyrene, 100 mm concrete block, 13 mm gypsum plastering	0.25	0.6	19 mm asphalt, 13 mm fibreboard, 205 mm XPS extruded polystyrene, 100 mm cast concrete	0.15	0.7

Table 3-3 Thermal properties of main materials used in the simulation

Material	Thermal conductivity W/m·K	Density kg/m^3	Specific heat J/(kg·K)	Volumetric heat capacity J/(m^3·K)
Brick	0.72–0.84	1700–1920	800–840	1.36×10^6–1.61×10^6
Concrete (block, reinforced, cast)	0.51–2.5	1200–2400	1000	1.20×10^6–2.40×10^6
XPS	0.034	35	1400	4.9×10^4
Gypsum plasterboard	0.25	900	1000	9×10^5
Asphalt	0.7	2100	1000	2.1×10^6

Ventilation rates

Two levels of ventilation rates were studied. According to Australian Standard 1668.2 (1991), the minimum outdoor airflow rate for classrooms serving students over 16 years of age where an air cleaning unit is not provided is 10 L/s/person. Another level of ventilation rate for simulation was a best practice of 50% increase above minimum, which is 15 L/s/person.

To summarize, simulation scenarios in this study combined 3 off cycle fractions, 2 cycling periods, 2 cooling setpoint temperatures, 2 envelope thermal performance levels and 2 ventilation rates shown in Table 3-4, yielding 48 simulation cases. Lecture Theatre 2 (highlight in white in Figure 3-2) was selected as the test bed of the DLC event simulation since it is located in the north-west of the building, representing a “worst case” scenario in the late Australian summer afternoon. The DLC event lasted for 3 hours from 2 pm to 5 pm. It was assumed that Lecture 2 held 130 students; the lighting load was 3 kW and equipment load 0.6 kW. Internal loads and schedules for other lecture theatres or spaces in the building remain the same as in the validation model described above. Direct load control was imposed on the original HVAC systems by setting up a cycling schedule to the chilled water loop. Assumptions for thermal comfort simulation are: the clo value for all occupants is 0.5 (0.4 for clothing and 0.1 for chairs). The Metabolic Rate is 1.2 Met for sedentary occupants reading and typing. The indoor air speed is the default value in DesignBuilder—0.137 m/s.

Table 3-4 Factors and levels of values for the simulation study

Levels of parameters	Off cycle fraction (%)	Cycling periods (h)	Cooling setpoint temperature preceding DLC Event, (°C)	Building envelope thermal performance levels	Ventilation rate (L/s/person)
Low	33	0.5 h	22	Poor	10
Medium	50	-	-	-	-
High	67	1h	24	Good	15

3.3. Design of Experiments (DOE)

Experiment is a systematic procedure carried out under controlled conditions to study the effects of parameters as they are set at various levels. Design of experiments (DOE) determines the allocation and method of experiments to satisfy the objectives (Park, 2007). There are some basic components and terminologies in DOE. Factors, or inputs to the process, are sources that affect the experiment. Levels refer to the different values that a factor can have in the study. Response, or outcomes/ characteristics, is an experimental result or output from the system (Design of Experiments, accessed 20-03-2016). In this study, "factor" refers to the parameters that have been identified to have influence in the thermal environments during DLC events in Table 3-4. "Level" refers to the low, medium or high values of the factors. The "response" or outcome of the experiment denotes subjects' thermal comfort responses and cognitive performance scores.

3.3.1. Three approaches to DOE

There are several commonly used DOE strategies that will be discussed in the following.

- One-factor-at-a-time experiments

The "one-factor-at-a-time" approach is the traditional method used by scientists and engineers. Researchers will thoroughly study all the factors one by one until they have been well characterized. This approach has been successful in developing a scientific understanding of the effect of a parameter and can be used to test many levels of a factor under precision conditions. However, its obvious drawback is that it is very time-consuming and expensive. It requires a lot of resources (experiments, time, material, etc.) for the amount of information obtained. Another major limitation of "one-factor-at-a-time" approach is that *interactions* are not estimable. An interaction between two factors means that the effect of one factor on the response depends on the level of another factor. Engineers often perform a hit-and-miss scattershot sequence of experiments from which it may be possible to estimate interactions, but they usually do not estimate them (Czitrom, 1999).

- Full factorial experiments

In a full factorial experiment, responses are measured at all combinations of the experimental factor levels, thus maximizing the possibility of finding a favourable result. Each combination of factor levels represents the conditions, or "runs", at which a response measure will be taken. In a full factorial experiment, the sample size is the product of the numbers of levels of the factors, which may result in a prohibitive number of runs. Consequently, full factorial experiments are only practical with small numbers of factors and levels. Because the costs of simulation are relatively low, the study reported in Section 3.2.3 is a full factorial design.

- Orthogonal array experiments (fractional factorials)

In real practice, there is no need to investigate *every* combination of factor levels to find the optimum one. By looking at the factor's average effect on the response, the optimum level for each factor can be safely inferred.

Dr. Genichi Taguchi is a Japanese statistician who pioneered techniques to improve quality through *Robust Design* of products and production processes. Dr. Taguchi developed fractional factorial experimental designs that use a very limited number of experimental runs. The experimental design employed by Taguchi, known as *orthogonal arrays*, is a simple and useful tool for planning industrial experiments since it requires only a fraction of the full-factorial combinations. An orthogonal array is a matrix of numbers arranged in rows and columns. Each row represents the levels (or states) of the selected factors in a given experiment, and each column represents a specific factor whose effects on the output (or response) are of interest to the experimenters (Antony & Kaye, 2012). The arrays are designed to handle as many factors as possible in a certain number of runs. The columns of the arrays are balanced and orthogonal. This means that in each pair of columns, all factor combinations occur the same number of times. Orthogonal designs allow you to estimate the effect of each factor on the response independently of all other factors.

The convention for naming the fractional factorial orthogonal arrays is $L_a\,(b^c)$ where *a* denotes the number of experimental runs, *b* refers to the number of levels for each factor and *c* is the number of columns in each array.

For example, if one wants to conduct an experiment to understand the influence of 4 different independent variables with each variable having 3 levels of values, then an L_9 orthogonal array (Table 3-5) might be the right choice. There are totally 9 experiments to be conducted and each experiment is based on the combination of level of values as shown in Table 3-5. For example, the third experiment is conducted by keeping the independent design variable 1 at level 1, variable 2 at level 3, variable 3 at level 3, and variable 4 at level 3. This array assumes no interaction effect between any two factors.

Table 3-5 $L_9\,(3^4)$ orthogonal array

	Independent Variables				Performance Parameter Value
Experiment #	Variable 1	Variable 2	Variable 3	Variable 4	
1	1	1	1	1	p1
2	1	2	2	2	p2
3	1	3	3	3	p3
4	2	1	2	3	p4
5	2	2	3	1	p5
6	2	3	1	2	p6
7	3	1	3	2	p7
8	3	2	1	3	p8
9	3	3	2	1	p9

Robust design assumes that the main effects are strong enough to stand out from the random noise (experimental error) and that they are stronger than interactive effects between the control factors (Fowlkes & Creveling, 2012). With orthogonal arrays, the philosophy towards interaction effects is different. Unless an interaction effect is explicitly identified a-priori and assigned to column in the orthogonal array, it is assumed to be negligible. That is to say, unless assumed otherwise, interactions at all levels are assumed to be negligible.

3.3.2. Orthogonal array for human subject experiments

A full factorial design of 48 simulation cases representing different thermal environments induced by various DLC events in university lecture theatres has been generated in the above simulation study. These simulated DLC events need to be replicated in a controlled environmental chamber so that human subjects' thermal comfort response and cognitive performance during exposure to these DLC events can be tested. However, it is neither affordable nor necessary to test all 48 DLC event scenarios with human subjects. Thus, the orthogonal array design has been applied to minimise the number of experiments that could give the full information about all factors that affect the output.

In this experimental design, since ventilation rate was found to have the smallest impact on thermal environments during DLC events compared with 4 other parameters (will be discussed in Chapter 4), the current experiments maintained a constant ventilation rate of 10 L/s/person, deemed typical for Australian university lecture theatres.

A mixed level orthogonal array of L_8 (2^4, 4^1) (shown in Figure 3-5) was adopted to test a single factor (off-cycle fraction) with 4 levels and 4 other factors (cycling period, cooling setpoint temperature, building envelope thermal performance and a blank factor with 2 levels). In Figure 3-5, each column denotes a factor and each row represents a combination of different factors in an experiment. A two-level factor has two values: 0 and 1, and a four-level factor has four values: 0, 1, 2 and 3. Apart from the three off-cycle fractions tested, 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. This experimental design only investigated the main control factor effects while interaction effects were ignored. Combinations of all factors and levels of values tested in each experimental condition were listed in Table 3-6.

$L_8(2^4,4^1)$, total number of experiments=8
Experiment 1: 0, 0, 0, 0, 0
Experiment 2: 0, 0, 1, 1, 2
Experiment 3: 0, 1, 0, 1, 1
Experiment 4: 0, 1, 1, 0, 3
Experiment 5: 1, 0, 0, 1, 3
Experiment 6: 1, 0, 1, 0, 1
Experiment 7: 1, 1, 0, 0, 2
Experiment 8: 1, 1, 1, 1, 0

Figure 3-5 A mixed level orthogonal arrays of $L_8\,(2^4, 4^1)$

Table 3-6 Factors and levels of values tested in the human subject experiments

Experiment	Conditions	Off cycle fraction (%)	Cycling period (h)	Cooling setpoint temperature before DLC event (°C)	Building envelope thermal performance
Experiment 1	Condition 1 (Control)	0%	0.5	22	Poor
	Condition 2	50%	0.5	22	Good
	Condition 3	67%	1	22	Poor
	Condition 4	33%	1	22	Good
Experiment 2	Condition 5	33%	0.5	24	Poor
	Condition 6	67%	0.5	24	Good
	Condition 7	50%	1	24	Poor
	Condition 8 (Control)	0%	1	24	Good

3.4. Laboratory Experiments with Human Subjects

3.4.1. 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 a tablet computing device. The temperature conditions in the chamber were controlled by a constant air volume system that can adjust air temperature within the occupied zone from 16 ºC to 38 ºC. The fresh air supply was constant at 10 L/s/person during the experiments.

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—30.8 ºC for this case. Other technical details about the laboratory can be found in de Dear et al. (2012).

3.4.2. Panel of subjects

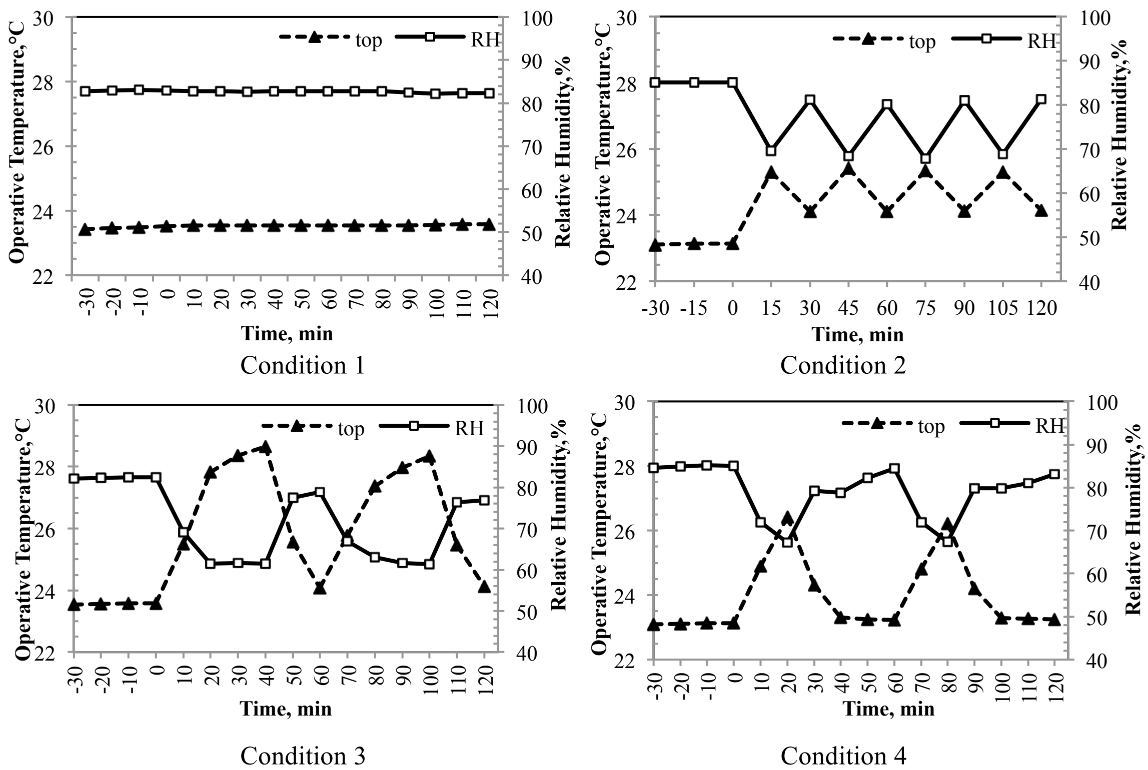
Two separate experiments on simulated DLC air-conditioning events with different adapting temperatures were performed. Fifty-six subjects (28 males and 28 females) for the two experiments were recruited from the university students, regardless of age, degree and discipline, 28 subjects (14 males and 14 females) for each. They aged 18–47 years (mean age 25 years) and were well balanced across humanities and engineering disciplines. Key anthropometric characteristics of the subject are listed in Table 3-7. Participants were required to wear a standard clothing ensemble for the experiments, consisting of a short-sleeve T-shirt, walking shorts, underwear, and sandals. T-shirts and walking shorts were provided by the researchers. 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. T-shirts and shorts were 100% polyester to avoid any transient absorption and desorption heat effects. Participants were paid at a fixed hourly rate. To increase participants' motivation and encourage them to take the cognitive tests seriously, they were informed before experiments that a prize would be awarded to the subject with the highest total cognitive performance score.

Table 3-7 Anthropometric characteristics of experiment participants (mean ± standard deviation)

Sex	Number	Age (year)	Height (cm)	Weight (kg)	DuBois Area (m^2)
Experiment 1					
Male	14	24.4 ± 4.8	178.1 ± 5.9	79.8 ± 18.9	1.97 ± 0.21
Female	14	27.0 ± 8.1	162.8 ± 7.4	53.9 ± 5.3	1.57 ± 0.11
Total	28	25.7 ± 6.7	170.5±10.2	66.8 ± 19.0	1.77 ± 0.26
Experiment 2					
Male	14	24.1 ± 6.4	174.9 ± 4.1	73.4 ± 9.3	1.88 ± 0.12
Female	14	24.6 ± 6.5	162.9 ± 7.1	56.5 ± 7.0	1.60 ± 0.12
Total	28	24.4 ± 6.3	168.9 ± 8.4	65.0 ± 11.8	1.74 ± 0.19

3.4.3. Conditions tested

Table 3-6 displays 8 environmental exposures in two experiments. Each participant has to experience four conditions. Instead of fully randomising four conditions, arrangements were made that participants experienced one control condition (fixed temperature with no DLC event) and three different experimental conditions (DLC events) starting from the same cooling setpoint temperature in each experiment. This arrangement makes it possible to examine the impacts of DLC events compared with control conditions and DLC events with different algorithms. All four conditions in Experiment 1 had a cooling setpoint temperature (air temperature) of 22 °C but this was raised to 24 °C in Experiment 2. The simulated operative temperature (t_{op}) and relative humidity (RH) for each condition were illustrated in Figure 3-6 and Figure 3-7. In order to replicate these temperature profiles in the climate chamber, the experimenter toggled between cooling and heating in the BMCS control. For a requirement of an instant temperature rise, additional portable heaters were also adopted as an aid.



Condition 1

Condition 2

Condition 3

Condition 4

Figure 3-6 Simulated operative temperature (t_{op}) and relative humidity (RH) in four conditions of Experiment 1

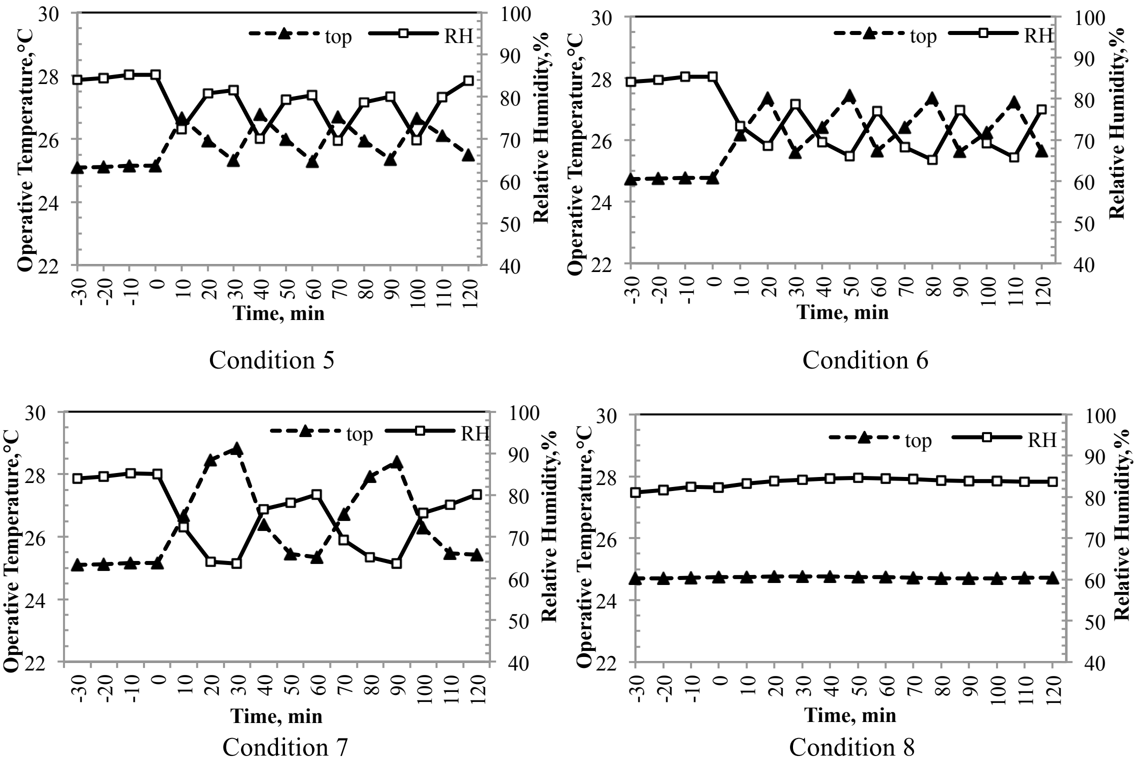


Figure 3-7 Simulated operative temperature (t_{op}) and relative humidity (RH) in four conditions of Experiment 2

3.4.4. Measurements

Physical and comfort measurements

During the experiments, the air temperature, globe temperature, relative humidity and air speed were measured every five minutes throughout every session. The globe temperature was measured at 0.6 m height within the occupied zone using thermistors (± 0.2 °C accuracy) inserted in 38 mm Ping-Pong balls painted malt black and served as the control sensor to implement the temperature cycles as depicted in Figure 3-6 and Figure 3-7; the air temperature was measured at 1.1 m height in the occupied zone by INNOVA 1221-Thermal Comfort Data Logger; wall-mounted humidity sensors at 1.7 m height monitored atmospheric moisture in the chamber. Seven fast-response Dantec thermal anemometers (Omnidirectional Transducer 54T21) were mounted at 1.1 m height adjacent to each subject where they measured air speed at a sampling rate of 1 Hz. 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 (with continuous slider scale to enable real TSV numbers), and a binary thermal acceptability scale. At the end of every session, subjects were presented with a binary overall acceptability question asking about each experimental session's thermal acceptability as a whole. These two questionnaires were administered to participants through a bespoke iPad application.

Cognitive performance measurements

Cognitive learning is a complex process that involves remembering, understanding, applying, analysing, evaluating and finally creating (Anderson et al., 2001). It 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. Although Dumont (1996), Hiltz and Wellman (1997) reported student grades as the most prevalent measure of cognitive learning outcomes, Rovai et al. (2009) argued that using grades as the sole measure of learning can be problematic, particularly when measuring learning outcomes across disparate courses and content areas.

Based on a century of scientific research, it is believed that the general cognitive ability or *g*, predicts a broad spectrum of important life outcomes, behaviours, and performances including academic achievement (Brand, 1987; Gottfredson, 1997; Jensen, 1998; Lubinski, 2000; Kuncel et al., 2004). Although there is no standard test for measuring university student's academic learning performances and professional capabilities, the generic cognitive skills underlying all learning can be reliably measured and can serve as "predictors" of university students' academic learning performances in lecture theatres. In this study, four generic cognitive skills were tested—memory, attention, reasoning and planning. Two short online cognitive performance tests were selected for each skill. All 8 tests used in this study (Figure 3-8) came from the public website of Cambridge Brain Sciences (CBS) Inc.[6].

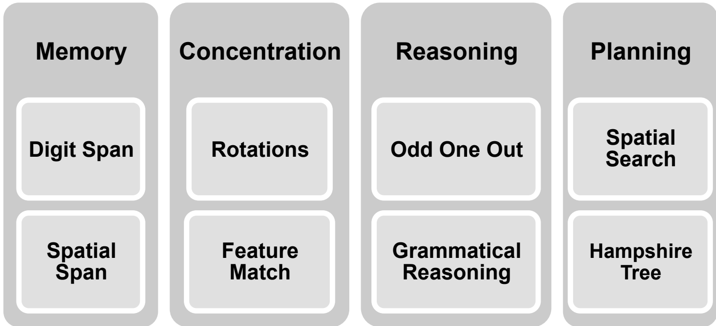


Figure 3-8 Cognitive performance tests adopted in each cognitive skill in current experiments

For memory skill, the *Digit Span* task tests subjects' verbal working memory by remembering a sequence of numbers those appear on the screen one after the other. Depending on whether the participant correctly remembers all the numbers, the next list of numbers will be either one number longer or one number shorter. The test ends after 3 errors and the outcome score is the maximum level achieved. 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. Difficulty is also dynamically varied according to participants' answers. The test ends after 3 errors and again the outcome measure is the maximum level achieved. For concentration skill, the *Rotations* test has two grids of coloured squares with one of the grids rotated by a multiple of 90 degrees. Participants must indicate whether the grids are identical, solving as many problems as possible within 90 seconds and the outcome is the total score. 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. Participants need to solve as many problems as possible in 90 seconds and the outcome measure is the total score. In reasoning skill, the *Odd One Out* task requires participants to work out which of

6 http://www.cambridgebrainsciences.com/.

the nine patterns is the odd one out and solve as many problems as possible in 90 seconds. The outcome measure is the total correct. 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 order to achieve maximum points, the participant must solve as many problems as possible within 90 seconds and the outcome measure is the total score. In planning skill, the *Spatial Search* is based on a test that is widely used to measure strategy during search behaviour (Collins et al., 1998). Some boxes are displayed on the screen in random locations within an invisible 5 × 5 grid. The participant must find a hidden "token" by clicking on the boxes one at a time to reveal their contents. On any given trial, the token will not appear within the same box twice. After 3 errors the test ends and the outcome measure is the maximum level achieved. The *Hampshire tree* task is an adaptation of the *Tower of London/ Tower of Hanoi* test (Shallice, 1982; Simon, 1975), which is a widely used clinical neuropsychological tool for assessing planning abilities. Numbered beads are positioned on a tree shaped frame. The participant repositions the beads so that they are configured in ascending numerical order running from left to right and top to bottom of the tree. Participants must solve as many problems as possible in as few moves as possible within 3 minutes and the outcome measure is the total score. Complete descriptions of the 8 cognitive performance tests can be found in the Supplemental Information from Hampshire et.al. (2012).

3.4.5. Experimental procedure for human subject tests

In each experiment, 28 subjects were divided into 4 sub-groups. Each sub-group had 7 subjects sitting in the climate chamber simultaneously. The occupant density was approximately $9m^2$/subject. The sequences at which sub-groups were exposed to different experimental conditions were balanced by *4×4 Latin-square design*.

The experiments were conducted in the summer of 2014 so that subjects were assumed to be naturally heat acclimatized. 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 setpoint temperature (air temperature 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 were administered to subjects via a digital tablet device every 5 minutes until the session ended. In the majority of 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 Figure 3-9) 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.

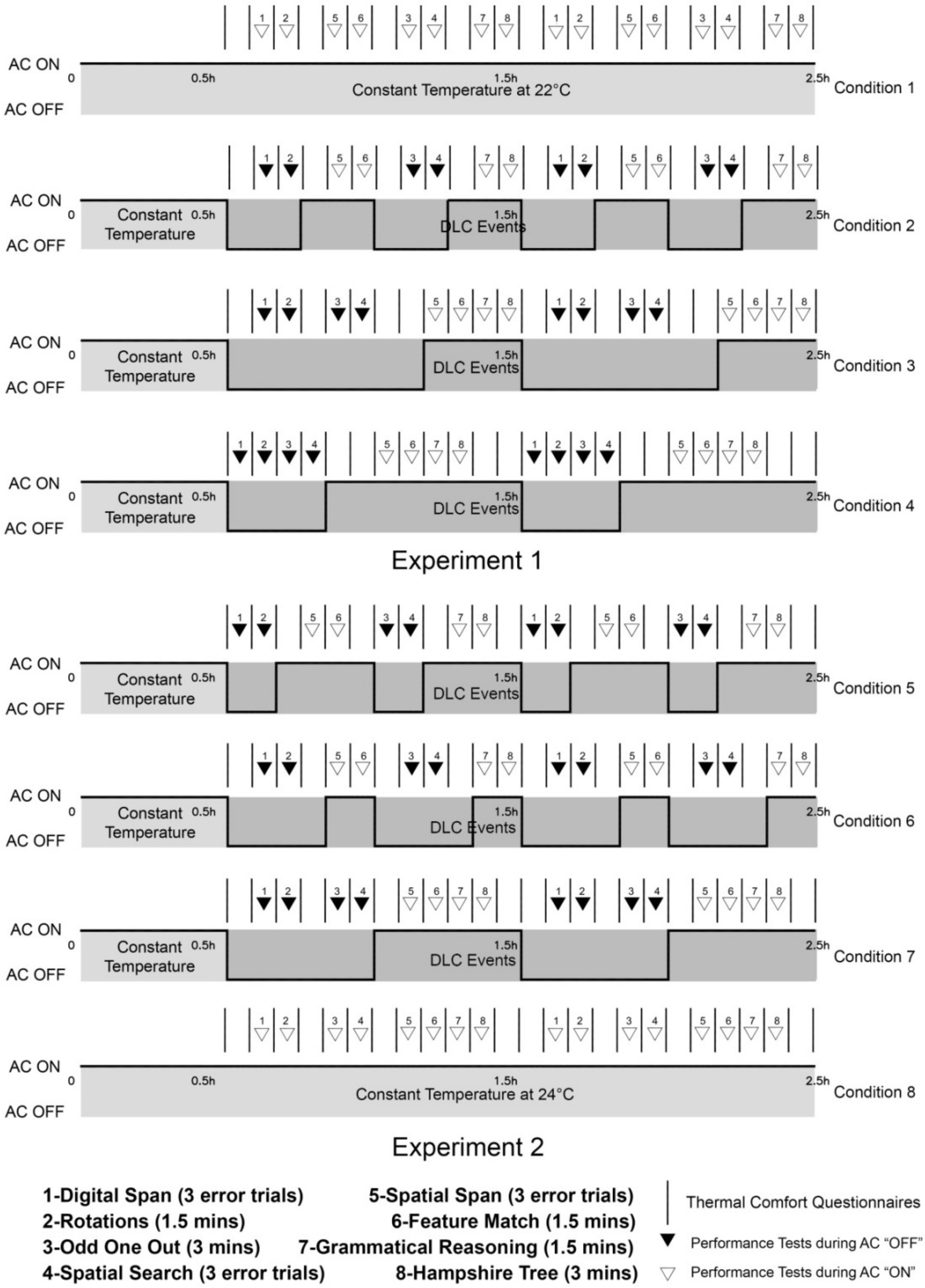


Figure 3-9 Experimental schedule for two experiments and timing of 8 cognitive performance tests

3.5. Statistical Analysis

Since observations within the same individual are usually correlated, this data structure violates the independence assumption required by traditional statistical analyses such as ANOVA and ordinary least-squares (OLS) multiple regression. Analysing data with hierarchical structures as if they are all on the same level leads to both interpretational and statistical errors. If multilevel data are analysed using single-level model and there is dependence of errors, Type I error (rejection of a null hypothesis that is actually true) can be dramatically increased (Tabachnick & Fidell, 2012). Thus, significant effects of treatment cannot be trusted if independence of errors is assumed without justification. For example, in a major study, Bennett (1976) uses a single-level model to assess whether "teaching styles" affected test scores for English, reading and mathematics at age 11. He found that teaching style significantly influenced progress, resulting in a call for a return to "traditional" or formal methods. However, this study did not take account of dependency in the scores of students from the same classes. In a multilevel analysis, it was subsequently found that the effects of teaching styles were not significant.

3.5.1. Multilevel linear modelling

Repeated measurements of the same subjects can be viewed as a hierarchical structure, where multiple observations are nested within individuals. Multilevel linear modelling (MLM, also known as hierarchical linear models or mixed linear models) is designed to deal with the violation of the assumption of independence of errors expected when individuals within groups share experiences that may affect their responses or there are repeated measures for same individuals. 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.

This experimental study is a three-level *repeated cross-sectional* design (LEMMA, accessed 20-03-2016): thermal environments were clustered within experiment conditions, which are in turn clustered within participants (Figure 3-10). Each participant attended the same four experimental conditions (including a control condition) in which the subject was exposed to various thermal environments (decided by the specific DLC event). The Level 1 variables are thermal environmental parameters such as operative temperature, air speed, relative humidity, etc. and time variables when the above parameters were measured. The Level 2 variable is the experimental condition. The Level 3 variables are demographic variables, i.e. age, sex. The dependent variables are subjects' thermal sensation, thermal acceptability, overall acceptability and cognitive performance. The purpose of MLM analysis is to find out whether the three levels of variables—thermal environmental parameters, different experimental conditions (control condition and 3 DLC conditions) and subjects' demographic variables have significant impacts on participants' thermal sensation, thermal acceptability, overall acceptability and cognitive performance. Some important cross-level interaction effects are also tested.

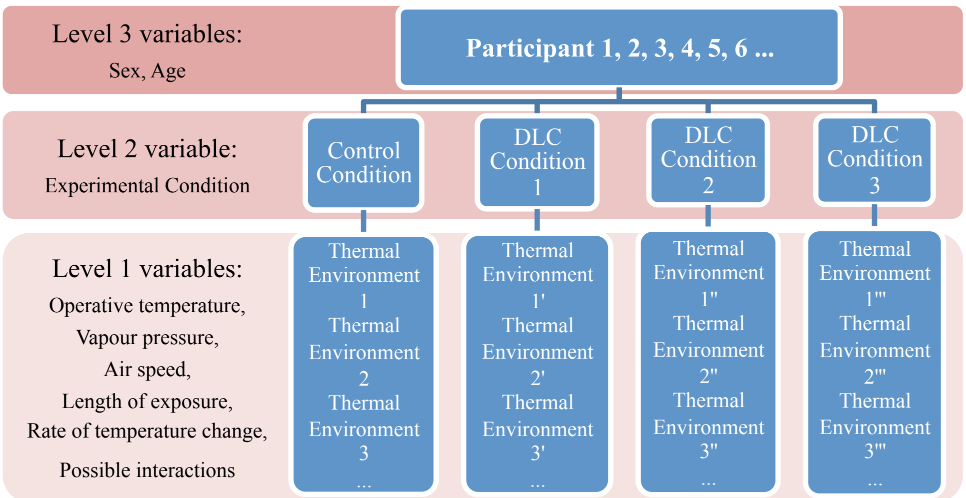


Figure 3-10 Hierarchical structure of the human subject experimental data

In MLM, responses from a subject are thought to be the sum (linear) of *fixed* and *random* effects (Field, 2013). If an effect has an impact on the population mean, it is a fixed effect; if an effect is associated with a sampling procedure (e.g., subject effect), it is a random effect. In MLM, random effects contribute only to the *covariance structure* of the data. The covariance structure specifies the form of the variance-covariance matrix in which the diagonal elements are variances and the off-diagonal elements are covariances (Field, 2013). It's useful to run the model with different covariance structures and use the goodness-of-fit indices to see whether changing the covariance structure improves the fit of the model. The presence of random effects, however, often introduces correlations between cases. Though the fixed effect is the primary interest in most studies or experiments, it is necessary to adjust for the covariance structure of the data.

Only fixed effects were the research interest in this study for both thermal comfort analysis and cognitive performance analysis; yet, the covariance structure of the data was adjusted to optimise the fit of the model. For the cognitive performance analysis, *sequence effect*, a common confounder for within-subject designs, was also 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. Multilevel linear modelling of participants' thermal sensation was implemented through *SPSS Mixed Models*, Version 22. Multilevel logistic modelling of participants' thermal acceptability and overall acceptability was implemented by *glmer* function in R, Version 3.2.0.

Subtracting a mean from each predictor score—"centring" it, changes a raw score to a deviation score. One major justification for doing this is to prevent multicollinearity when predictors are components of interactions or raised to powers; also centring can facilitate interpretation when there is no meaning to a value of zero on a predictor (Tabachnick & Fidell, 2012). Thus, Level 1 variables that do not have a meaningful zero point were centred by their respective grand means (Tabachnick & Fidell, 2012). Table 3-8 listed the variables that have been centred and their grand means in each experiment. 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.

Table 3-8 Centring predictors by their grand means in two experiments

Centred predictors	Experiment 1	Experiment 2
centred operative temperature (°C)	operative temperature – 24.7	operative temperature – 25.9
centred vapour pressure (kPa)	vapour pressure – 2.23	vapour pressure – 2.37
centred air speed (m/s)	air speed - 0.06	air speed – 0.05
centred subjects' age (yr)	age – 25.7	age – 24.4

3.5.2. Evaluation of assumptions

MLM is an extension of multiple linear regression, so the limitations and assumptions for multiple linear regression apply to all levels of the analysis. Univariate and multivariate outliers are sought for level-1 variables within each experimental condition based on Raudenbush & Bryk (2002)'s recommendation.

The *intra-class correlation* ϱ is an explicit measure of the dependence of errors because it compares differences between groups to individual differences within groups. If ϱ is trivial, there is no meaningful average difference among groups on the dependent variable, and data may be analysed at the individual (first) level. The larger the intra-class correlation, the greater the violation of independence of errors and the greater the inflation of Type I error rate if the dependence is ignored, which means the hierarchical structure of the data must be considered when choosing the appropriate analysis. Intra-class correlation for both experiments was calculated by running a three-level (thermal environments, conditions and participants) model through SPSS with random intercepts but no predictors (a three-level intercepts-only model). The intra-class correlation at the second level and the third level is shown in Equation 3-3 and Equation 3-4:

$$\rho_{L2} = \frac{\sigma_{L2}^2}{\sigma_{L1}^2+\sigma_{L2}^2+\sigma_{L3}^2} \quad \text{Equation 3-3}$$

$$\rho_{L3} = \frac{\sigma_{L3}^2}{\sigma_{L1}^2+\sigma_{L2}^2+\sigma_{L3}^2} \quad \text{Equation 3-4}$$

where σ_{L1}^2, σ_{L2}^2 and σ_{L3}^2 denote Level-1, Level-2 and Level-3 variances respectively.

The intra-class correlations for two experiments at the second and the third level are displayed in Table 3-9. In Experiment 1, roughly 26% of the variance in TSV was attributable to the second-level of hierarchy (experimental conditions), while only 1% of the variance was due to the third-level (personal differences). Experiment 2, however, displays the opposite trend—variance in TSV derived from experimental conditions (9%) was less than variance of participants (14%). It indicated that TSV of different participants within the same experimental condition were more correlated (similar) in Experiment 1 than in Experiment 2. In Experiment 2, the same participants tend to vote more similarly for different experimental conditions than in Experiment 1. Despite these differences, generally, the intra-class correlations for two experiments indicate the necessity of multilevel analysis with experiment condition as a random second-level unit and participant as a random third-level unit.

Table 3-9 Intra-class correlations at experimental condition and participant level in two experiments

Intra-class Correlation	Experiment 1	Experiment 2
ρ_{L2}	0.26	0.09
ρ_{L3}	0.01	0.14

4. Simulation of Direct Load Control Air-conditioning Events in University Lecture Theatres

In this chapter, DesignBuilder and EnergyPlus was used to simulate thermal environments inside a typical Australian university lecture theatre during DLC events under various off cycle fractions, cycling periods, cooling setpoint temperatures, building envelope thermal performance specifications and ventilation rates. The analysis also explored thermal comfort impacts by applying the PMV/PPD index to simulated indoor climates.

4.1. THERMAL ENVIRONMENT AND COMFORT DURING A DLC EVENT

To evaluate the thermal environments during a DLC event, the mean air temperature, zone mean radiant temperature (MRT), zone operative temperature and zone air relative humidity (RH) have been plotted from EnergyPlus. The widely used thermal comfort index—predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) have also been plotted to evaluate thermal comfort impacts of the DLC event.

Figure 4-1demonstrates thermal environment parameters for a DLC scenario with 50% off cycle fraction, 0.5 h cycling period, 22 ºC cooling setpoint temperature, good building envelope thermal performance and ventilation rate 10 L/s/person. Values were plotted every 15 minutes from 13:30 to 17:30, which was half hour before the DLC event to half hour after it. All four parameters have saw-tooth profiles. Before the event started, the mean air temperature settled near the cooling setpoint temperature 22 °C (air temperature). When the cooling was off, it drifted to around 26 °C in 15 minutes, and then came back to about 22 °C when cooling was back on. The MRT was about 2 °C higher than the mean air temperature before the event probably because of direct sunlight being cast on the western walls and roof. During the event, the fluctuation of MRT also lagged behind the mean air temperature for about 15 minutes and reached around 26 °C at peak. The operative temperature was the average of the mean air temperature and the MRT and ranged from 23 °C to 25.5 °C during the event.

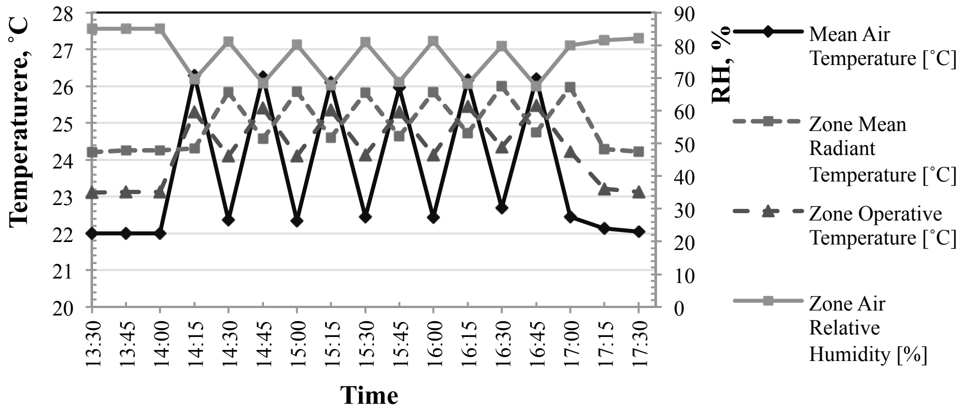


Figure 4-1 Thermal environment for 50% off cycle fraction, 0.5 h cycling period, 22 ºC cooling setpoint temperature, good building envelope thermal performance and ventilation rate 10 L/s/person

Regarding the RH, it was above 80% when cooling was on and dropped to 67% when cycled off. Although the simulated RH seems to be high in an air-conditioned building, several studies (Cummings & Withers, accessed 16-03-2016; Fischer, 1996; Morse et al., 2007) have provided evidence that high humidity problem is very common in school buildings during hot and humid weather, partly due to the high occupant density which requires high ventilation rates, and partly due to the poor dehumidification capability of commonly used AC systems in schools. According to Cummings & Withers (accessed 16-03-2016), if there is no latent cooling or internal moisture generation, the room RH would be 85% if the outdoor dewpoint temperature is 21 °C and the room temperature is 24 °C. It also points out that for chilled water AC units with constant volume fan and modulating chilled water valve (the control system in this case), as the cooling load diminishes, the flow of chilled water to the coil is reduced and the coil temperature rises, thus the ability of the coil to remove water vapor from the air declines and eventually disappears (at about 50% load factor). In this case, the chiller is oversized (the calculated cooling load is about 180 kW while the actual cooling capacity of the chiller is 300 kW). Besides, field measurements in October (very dry season in Sydney) have shown that the RH could be higher than 70% when the lecture theatre was populated with about 100 students. Based on above facts, the high humidity in the simulation results seems to be plausible. To ameliorate this situation, commonly adopted methods include the automatic fan-speed adjustment or installing a dedicated outdoor air system (DOAS); both could enhance the dehumidification capability of the HVAC system and maintain lower indoor RH during DLC events.

Figure 4-2 shows the PMV/PPD index values during the DLC event. Before the event starts, PMV fixed at -0.6, a little below the recommended comfort range of -0.5–+0.5 by (ASHRAE 55, 2013). It indicates that the cooling setpoint temperature of 22 °C, the common practice in air-conditioned buildings in Australia, is somehow low for sedentary occupants dressing in typical summer clothing. Along with the temperature rising when the cooling cycles off, PMV increased to around 0.4, still within the comfort range. PPD maintained around 13% when cooling was on and dropped to about 7% when cooling was off, indicating that in this DLC scenario, cycling on and off AC system at 15-min intervals from 22 °C has increased occupants' thermal comfort by mitigation of AC overcooling rather than decreasing comfort.

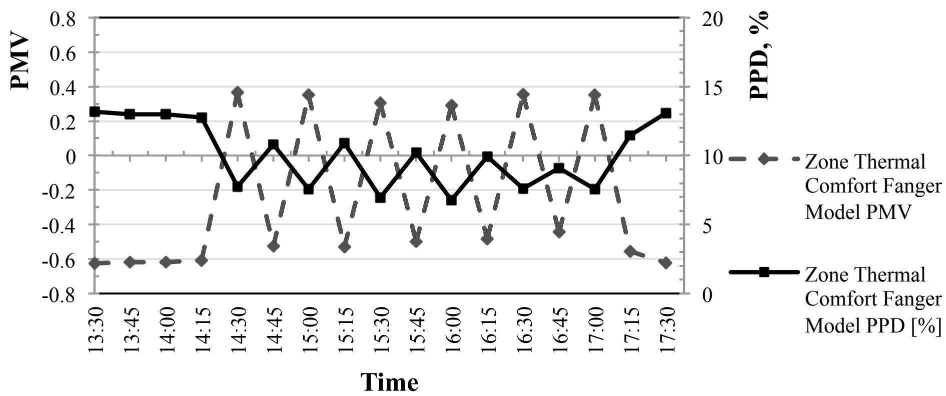


Figure 4-2 PMV/ PPD for 50% off cycle fraction, 0.5 h cycling period, 22 ºC cooling setpoint temperature, good building envelope thermal performance, and ventilation rate 10 L/s/person

4.2. EFFECTS OF DIFFERENT PARAMETERS ON THERMAL ENVIRONMENTS DURING DLC EVENTS

Figure 4-3 to Figure 4-6 illustrate operative temperature profiles simulated from various parameter values during DLC Events. In each figure, two parameters vary while the other three parameters were held constant. These figures demonstrate that all 5 parameters analysed had impacts on occupied zone thermal environments during DLC events. In order to find out which parameter had relatively larger influence, the maximum operative temperatures in all 48 simulation scenarios were analysed in relation to the levels of input parameters in question. One-way ANOVA test revealed that there was a significant difference between impacts of different parameters (p < 0.001). *Post hoc* procedure (Games-Howell) (Toothaker, 1993) was carried out to identify significantly different pairwise comparisons (Table 4-1). Across the range of parameter values tested, the impacts of cycling period variations were significantly larger than impacts of cooling setpoint temperature differences and building envelope thermal performance levels, which were in turn significantly greater than impacts of ventilation rate variations. Obviously the magnitude of impacts of various input parameters relates to the range of values tested. Any parameter value outside this range might result in the relative impacts being amplified. In addition, other factors which include HVAC system types, cooling loads and control modes can also be expected to have an impact. To make a general conclusion, in typical Australian university lecture theatres, off cycle fractions, cycling periods and cooling setpoint temperatures have relatively larger influences on occupied zone thermal environments during DLC events compared to building envelope thermal performance levels and ventilation rates.

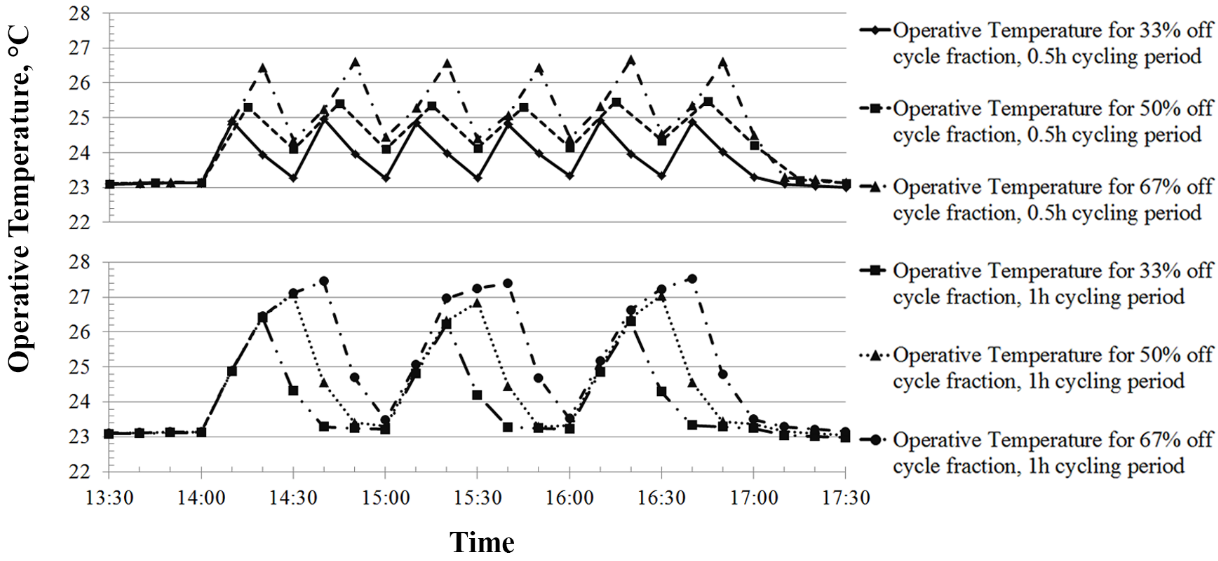


Figure 4-3 Operative temperatures for different cycling schemes under 22 ºC cooling setpoint temperature, good building envelope thermal performance, and ventilation rate 10 L/s/person

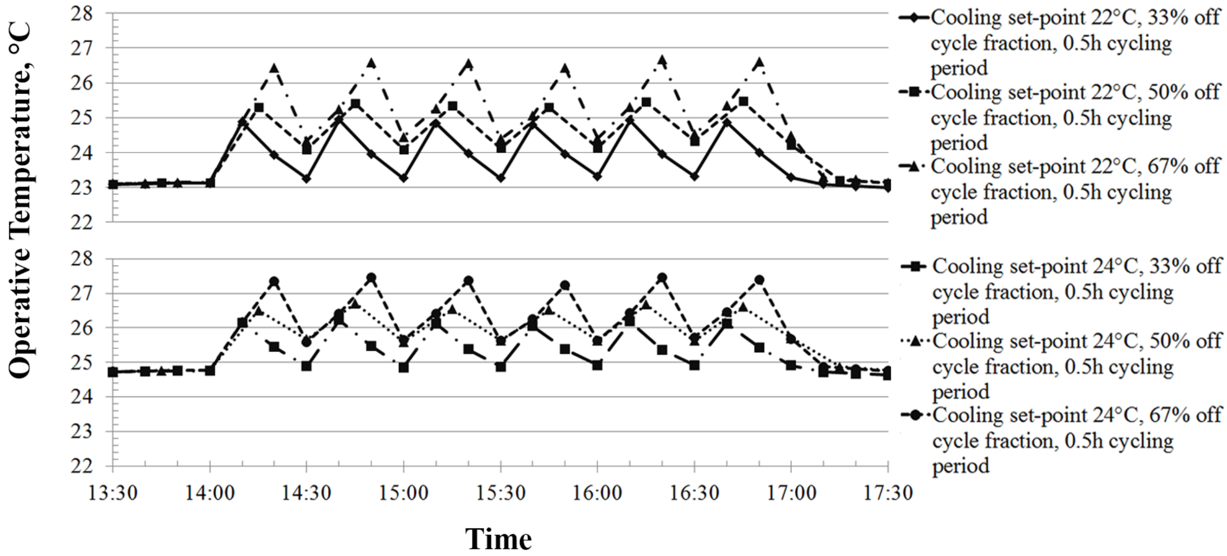


Figure 4-4 Operative temperatures for two cooling setpoint temperatures under three off cycle fractions with 0.5 h cycling period (good building envelope thermal performance, ventilation rate 10 L/s/person)

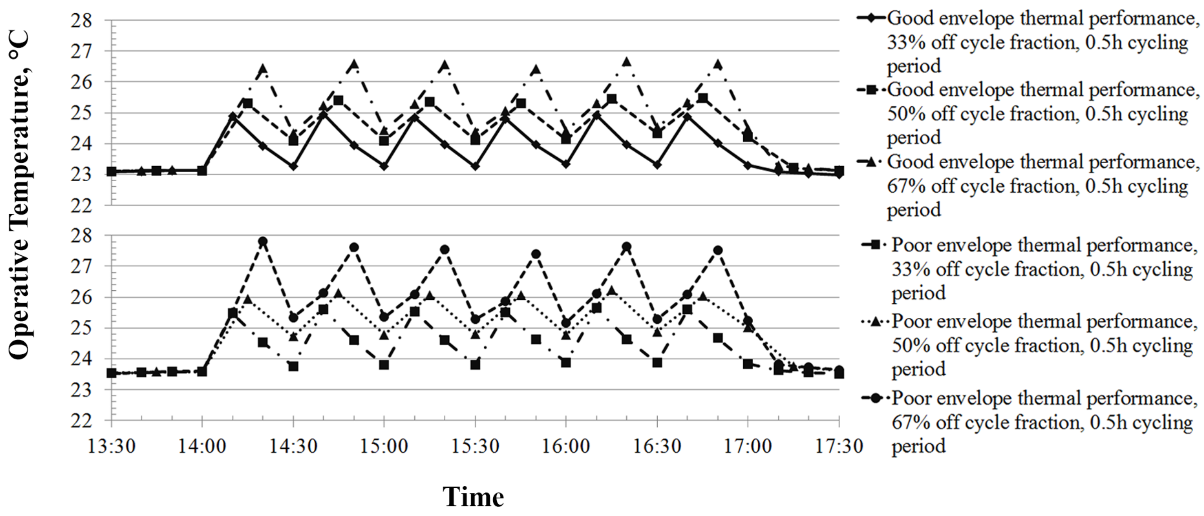


Figure 4-5 Operative temperatures for two different building envelope thermal performance levels under three off cycle fractions with 0.5 h cycling period (cooling setpoint temperature 22 °C, ventilation rate 10 L/s/person)

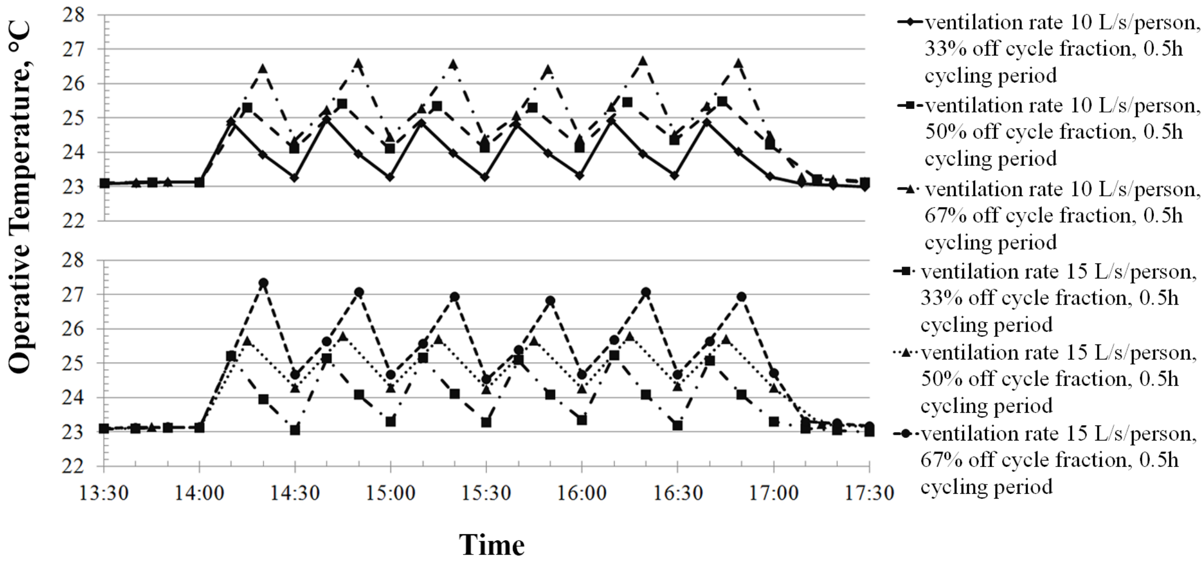


Figure 4-6 Operative temperatures for two different ventilation rates under three off cycle fractions with 0.5 h cycling period (cooling setpoint temperature 22 °C, good building envelope thermal performance)

Table 4-1 Pairwise comparisons of input parameter impacts on the maximum operative temperature during DLC events

(I) Condition	(J) Condition	Mean difference (I – J, °C)	Sig.
Impacts of off cycle fractions varied between 33% and 67%	Impacts of cycling periods varied between 0.5 h and 1 h	-0.03	1.000

	Impacts of cooling setpoint temperatures varied between 22 °C and 24 °C	0.48	0.051
	Impacts of building thermal performance levels varied between good and poor	0.47	0.047*
	Impacts of ventilation rates varied between 10 and 15 L/s/person	0.94	< 0.001**
Impacts of cycling periods varied between 0.5 h and 1 h	Impacts of cooling setpoint temperatures varied between 22 °C and 24 °C	0.51	0.002**
	Impacts of building thermal performance levels varied between good and poor	0.50	0.001**
	Impacts of ventilation rates varied between 10 and 15 L/s/person	0.97	< 0.001**
Impacts of cooling setpoint temperatures varied between 22 °C and 24 °C	Impacts of building thermal performance levels varied between good and poor	-0.01	1.000
	Impacts of ventilation rates varied between 10 and 15 L/s/person	0.46	< 0.001**
Impacts of building thermal performance levels varied between good and poor	Impacts of ventilation rates varied between 10 and 15 L/s/person	0.47	< 0.001**

(* p <0.05; ** p <0.01)

4.3. THERMAL COMFORT IMPACTS OF DLC EVENTS

Most contemporary thermal comfort standards are specified as an acceptable range of the relevant comfort index. They also stipulate that large temperature fluctuations not under the direct control of individual occupants should be avoided so as to keep thermal environment relatively static. However, above analysis show that duty cycle restriction in a DLC event will cause repeated rises and falls in air temperature, MRT and RH, creating dynamic thermal environments. Since the PMV/PPD model was derived in a controlled climate chamber under steady conditions, it might not be fully appropriate to assess thermal comfort impacts during DLC events, so in this study it serves merely as indicative comfort performance criterion. The actual thermal comfort impacts of DLC events can only be obtained from replicating simulated DLC events within climate chamber experiments with human subjects or in actual field studies.

4.3.1. ASHRAE 55-2013 permissible and simulated temperature changes for temperature drifts

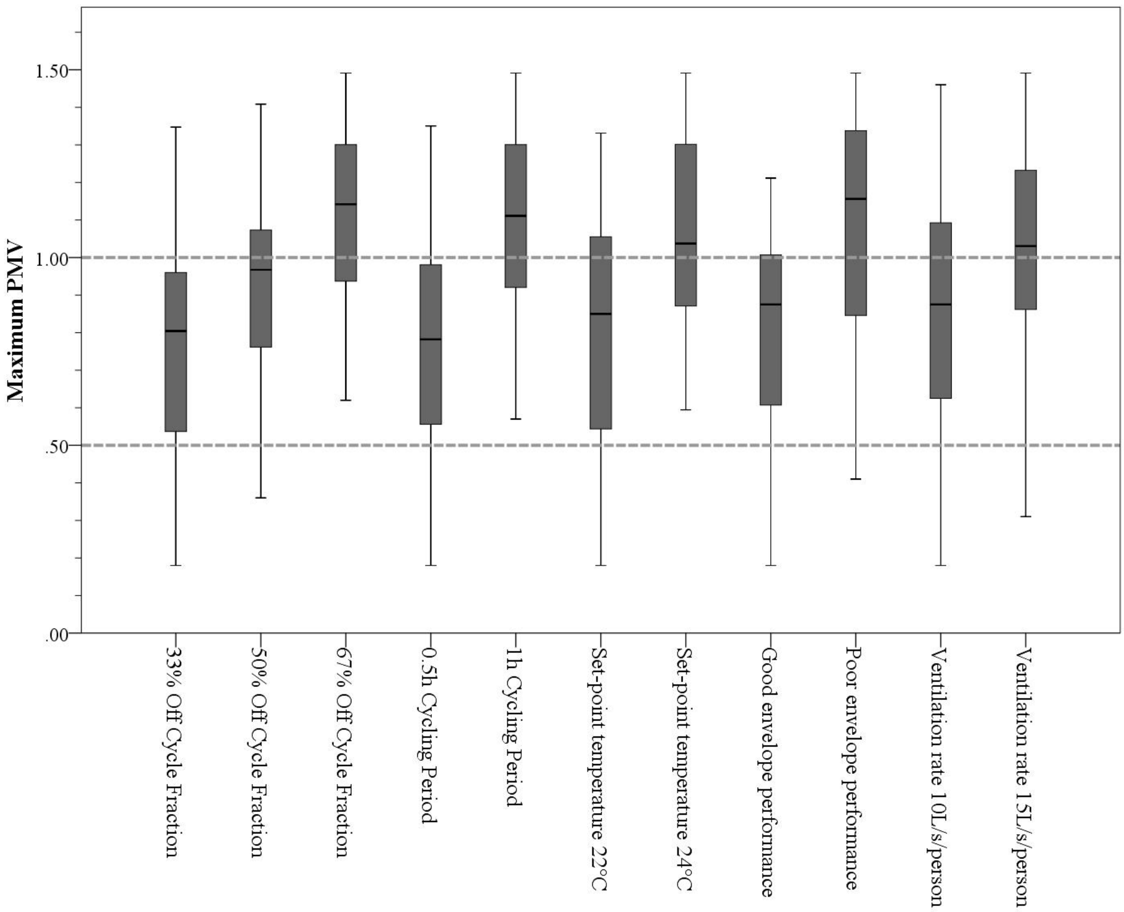
ASHRAE 55 (2013) (5.3.5 Temperature Variations with Time) requires that for cyclic variations with a period not greater than 15 min, the maximum allowable peak-to-peak variation in operative temperature is 1.1 °C; for temperature ramps and drifts, the maximum operative temperature change allowed during a period of time is shown in Table 4-2. Cyclic variations with a period greater than 15 min are assessed with the ramps or drifts criteria. Since the cycling periods for all DLC events under study are longer than 15 min, they should be treated as temperature drifts and should comply with the requirement in Table 4-2. Results indicate that simulated operative temperature changes within specific time periods during DLC events all exceeded the ASHRAE 55-2013 limits (see Table 4-2). Simulation results were grouped according to cooling setpoint temperatures. Duty cycle restriction in a DLC event causes temperature fluctuations that exceeded the ASHRAE standard.

Table 4-2 ASHRAE 55 (2013) permissible and simulated temperature changes for temperature drifts

Time period, h	Maximum operative temperature change allowed in ASHRAE 55-2013, °C	Maximum operative temperature change in simulation for 22 °C setpoint scenarios, °C	Maximum operative temperature change in simulation for 24 °C setpoint scenarios, °C
0.2	-	2.2	1.8
0.25	1.1	2.7	2.2
0.5	1.7	5.0	3.9
1	2.2	5.3	4.2

4.3.2. PMV/ PPD model as the thermal comfort index

As is stated in ASHRAE 55 (2013), PMV/PPD is widely used to determine the requirements for thermal comfort in occupied spaces. It recommends that PMV should be held within the range of -0.5 to +0.5 and PPD within 10%. Figure 4-7 illustrates a boxplot of maximum PMV/PPD in 48 scenarios pooled by different values of parameters. Across all DLC scenarios, the mean of maximum PMV is 0.9 ± 0.3 (SD). The maximum PMV in only part of the lower quartile values fell below +0.5. Generally speaking, the interquartile range of maximum PMV in parameters with low-level values (such as 33% off cycle fraction, 0.5 h cycling period, good envelope thermal performance, etc.) fell between the PMV range of +0.5–+1, while the upper half of maximum PMV in parameters with high-level values (67% off cycle fraction, 1 h cycling period, poor envelope thermal performance, etc.) all exceeded +1. The mean maximum PPD in 48 scenarios is 26.2% ± 10.3% (SD). It should be noted that the maximum PMV and PPD values during DLC events do not necessarily correspond to each other since in some cases such as the one stated in Section 4.1, the maximum PPD was achieved when AC was on and the PMV was very low due to AC overcooling. For this reason, even the lower quartile PPD values exceeded 10% (shown in Figure 4-7). Figure 4-7 also reveals that most DLC scenarios have exceeded the permissible thermal comfort range by PMV/PPD methods specified in ASHRAE 55-2013.



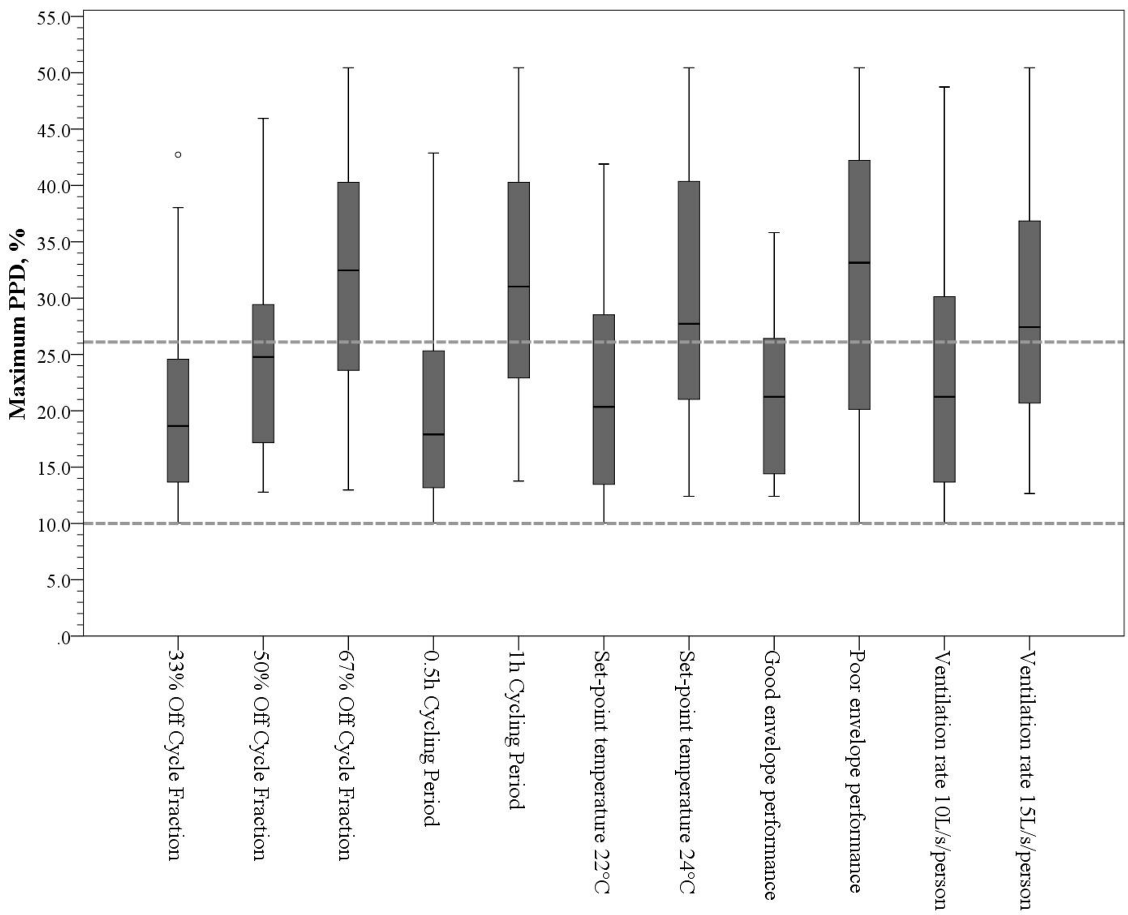


Figure 4-7 Boxplot of maximum PMV/PPD in 48 scenarios pooled by different values of parameters (maximum-75% percentile-median-25% percentile-minimum)

Though PMV/PPD may not be strictly appropriate for DLC events, previous laboratory studies on temperature transients have reported that moderate operative temperature changing rate of lower than 0.5 °C/h has no influence on thermal sensation or thermal comfort (acceptability) than in steady states (Griffiths and McIntyre, 1974; Berglund and Gonzalez, 1978a); for rate of change greater than 1 °C/h, subjects' thermal sensation generally agrees well with predicted by PMV model (tested up to ±5.0 °C/h) (Knudsen et al., 1989; Kolarik et al., 2009; Schellen et al., 2010). However, there is no consistent conclusion on the limit of the temperature changing rate within which PMV/PPD will be valid. Still, the suitability of PMV/PPD model for application to DLC events needs to be tested in laboratory experiments and field studies.

4.3.3. Optimizing DLC algorithms for university lecture theatres

The preceding analysis reveals that the majority of DLC scenarios tested had adverse thermal comfort impacts on the occupants. DLC scenarios with higher off cycle fraction, longer cycling period, higher cooling setpoint temperature, poorer building envelope thermal performance and higher ventilation rate will induce more occupant thermal discomfort during DLC events. Although a common practice in previous DLC programs, a standard or universal DLC algorithm for all participating premises will not guarantee universally acceptable thermal environments, and run the risk of increased override rates (Weller, 2011; Greenberg and Straub, 2008). In order to achieve acceptable thermal comfort outcomes, DLC algorithms must be applied judiciously and customized to the specific building. Selection of DLC algorithms in university lecture theatres or any other classroom buildings should take into account cooling setpoint temperatures, building envelope thermal performance as well as ventilation rates. Usually in an existing building, the construction type and ventilation rate are already set. If the buildings have relatively poor envelope thermal performance and high ventilation rates, only conservative DLC algorithms with low off cycle fraction, short cycling period and low cooling setpoint temperature should be selected; if the buildings have relatively good envelope thermal performance and moderate ventilation rate, more ambitious algorithms can be considered for higher peak demand reduction. However, cycling schemes combining 67% off cycle fraction with 1 h cycling period are not recommended for lecture theatres at any time.

Comparison of 24 pairs of simulation cases with the same off cycle fraction, setpoint temperature, building envelope thermal performance and ventilation rate, but different cycling periods (0.5 h vs.1 h) using the independent t-test revealed that the difference in maximum PPD during DLC events, -11.6%, was significant at $p < 0.001$, representing a large-sized effect (Cohen's $d = 1.22$). It suggested that, all else being equal, especially the off cycle fraction which determines the amount of load shedding, shorter cycling period DLC scenarios have less adverse thermal comfort impacts than longer ones. This could be another way of optimizing DLC algorithms. However in practice, cycling periods must not be so short as to cause compressor failures and inefficiencies (Zhang et al., 2013). The prevailing 0.5 h cycling period in previous DLC programs can serve as an ideal value.

4.4. CONCLUSIONS AND SUGGESTIONS

By simulating a exemplar university lecture theatre in DesignBuilder and EnergyPlus, this chapter has explored thermal environments and thermal comfort impacts of DLC events induced by various off cycle fractions, cycling periods, cooling setpoint temperatures, building envelope thermal performance and ventilation rates. The following conclusions can be drawn from this chapter:

- During DLC events, the air temperature, mean radiant temperature and relative humidity all fluctuate with the AC on and off, forming saw-tooth profiles. Though simulation results suggest high relative humidity, according to other studies, high humidity problems are very common in school buildings with poor dehumidification capability but located in hot and humid climate zones. Use of variable speed fans or dedicated outdoor air systems can enhance the dehumidification capability of the HVAC system and maintain lower indoor RH during DLC events, which will offset the adverse thermal comfort impacts of DLC due to high RH.
- All 5 parameters tested in this study have impacts on thermal environments during DLC events. Under tested conditions that represent exemplar Australian university lecture theatre settings, off cycle fractions, cycling periods and cooling setpoint temperatures have relatively larger influences compared to building envelope thermal performance and ventilation rates.
- Simulation results show that DLC scenarios do not comply with the limits on temperature ramps and drifts specified in ASHRAE 55 (2013). Most DLC scenarios have exceeded the permissible thermal comfort range by PMV/PPD method indicated in ASHRAE 55-2013. However, the PMV/PPD index is an

indicative-only thermal comfort index. Subjects' actual thermal comfort impacts of DLC events can only be obtained from laboratory experiments or field studies, which are the focus of future research by the authors.

- In order to maintain acceptable thermal comfort for occupants, DLC algorithms must be applied judiciously and customized to the specific building. Selection of DLC algorithms should take all influencing parameters into account and avoid disadvantageous parameter-combinations. University buildings with poor envelope thermal performance and high ventilation rate should adopt conservative DLC scenarios, while buildings with good envelope thermal performance and moderate ventilation rate can implement more radical DLC algorithms to achieve higher peak demand reduction. All else being equal, DLC algorithms with shorter cycling periods have less adverse thermal comfort impacts than the longer ones, and are therefore recommended for university lecture theatre applications.

5. University Students' Thermal Comfort under Temperature Cycles Induced by Direct Load Control Events

In this chapter, 56 subjects' thermal sensation and thermal acceptability were closely examined during 6 DLC conditions and 2 control conditions simulated in a climate chamber. Multilevel linear models were employed to find significant predictors for subjects' thermal sensation vote, thermal acceptability and overall acceptability during DLC events. Results from current experiments were compared with the limits of temperature cycles, ramps and drifts defined in ASHRAE 55 (2013); the validity of PMV/PPD model and thermal comfort zones during temperature cycles were also examined.

5.1. Measured Experimental Conditions

Figure 3-6 and Figure 3-7 illustrate the ideal experimental conditions based on simulation results. However, the targeted temperature and humidity profiles could not be fully realised during the laboratory experiments due to limited precision on HVAC control. 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 5-1, 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. The temperature range actually achieved for the control conditions (ideally a fixed air temperature) was approximately 2 °C.

Table 5-1 The recorded range of air temperature and ET, mean RH with standard deviation (sd) for each condition

Experiment	Conditions	Range of air temperature (°C)	Range of ET (°C)	Mean RH ± sd
1	Condition 1	21.3–23.7	19.7–22.7	75.1% ± 4.2%
	Condition 2	22.0–26.7	20.8–25.1	74.7% ± 4.5%
	Condition 3	22.2–31.2	20.5–28.6	68.2% ± 7.0%
	Condition 4	21.7–29.0	20.0–27.1	72.7% ± 5.0%

2	Condition 5	23.6–28.8	21.6–26.6	72.1% ± 4.8%
	Condition 6	23.1–29.7	21.1–27.4	69.7% ± 5.5%
	Condition 7	23.2–31.5	21.4–28.9	69.5% ± 5.9%
	Condition 8	23.0–25.5	21.4–24.1	75.4% ± 4.0%

5.2. THERMAL PERCEPTION DURING DLC EVENTS

Figure 5-1 illustrates subjects' average thermal sensation vote (TSV) in each condition during both experiments. By applying repeated-measures ANOVA, it was found that for both experiments, there were significant differences in the average TSV between variant conditions of test ($p < 0.001$ for both experiments). Significant pairwise comparisons were further detected by *Post hoc* analysis with *Bonferroni* correction and marked in Figure 5-1. In Experiment 1, average TSV in the control condition (-0.40) was significantly lower than those in three DLC conditions, and also, average TSV in Condition 3 (0.67) was significantly higher than those in Condition 1 (-0.40), 2 (0.11) and 4 (-0.10). In Experiment 2, average TSV in the control condition (0.15) was also significantly lower than those in three DLC conditions. Figure 5-2 plots subjects' average thermal acceptability within a session and overall acceptability for each condition in the two experiments and compares with the normative 80% thermal acceptability limit.

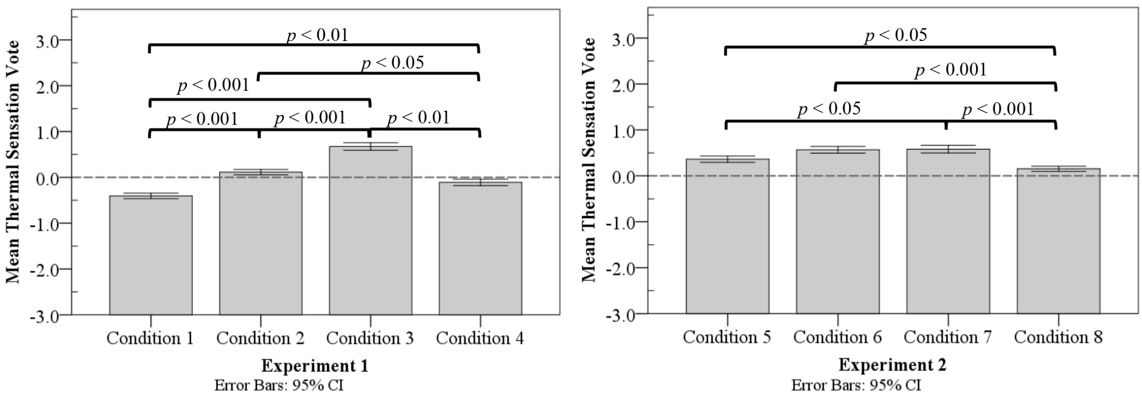


Figure 5-1 Average TSV for different conditions in Experiment 1 and 2

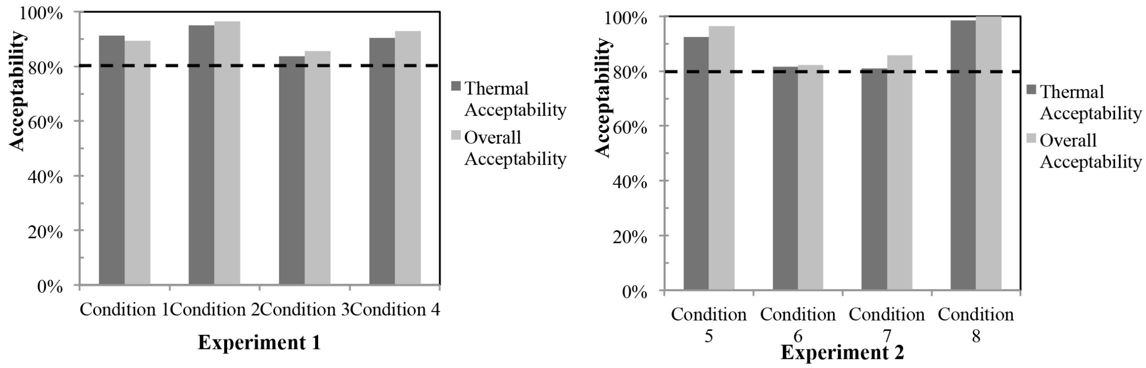
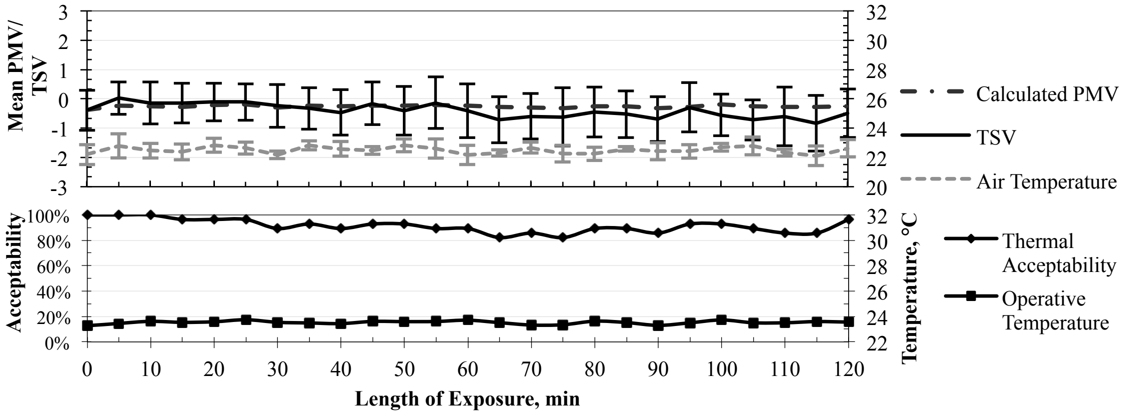
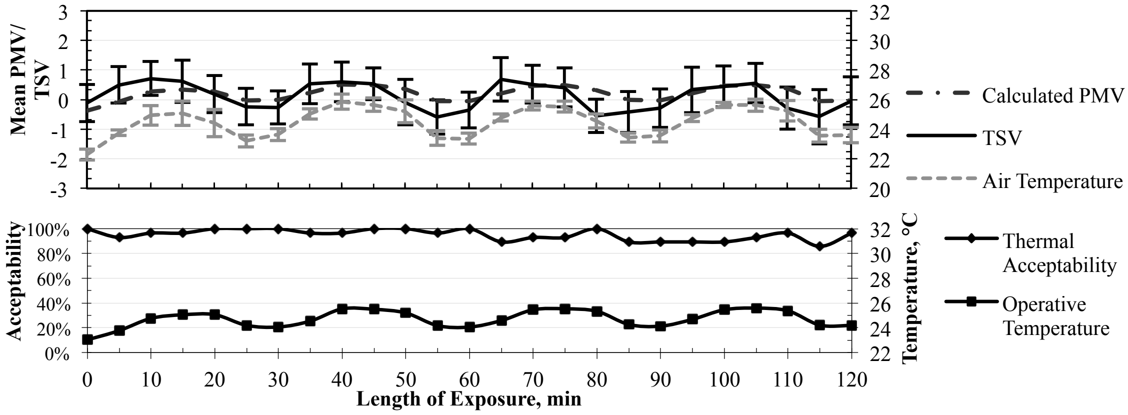


Figure 5-2 Average thermal acceptability and overall acceptability for different conditions in Experiment 1 and 2

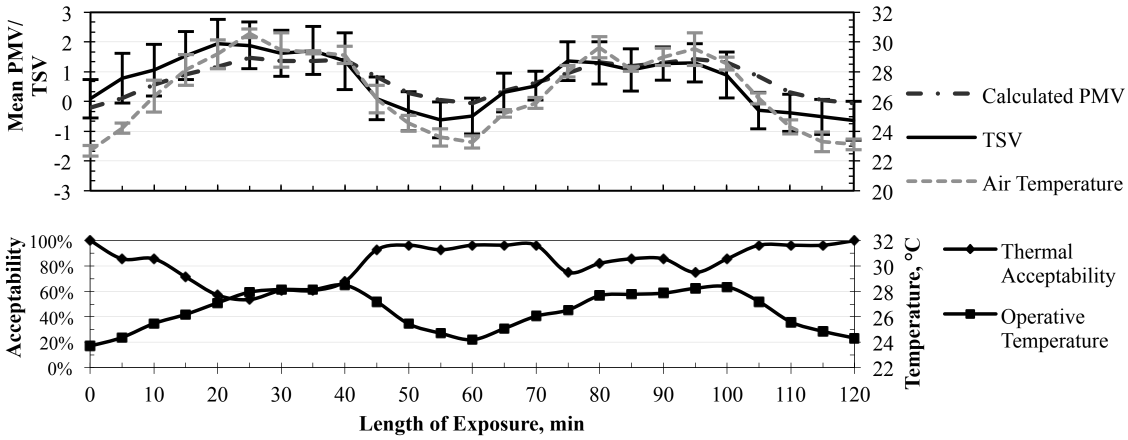
Figure 5-3 depicts the time series data for air temperature and operative temperature monitored in the climate chamber for 8 conditions in two experiments, along with subjects' TSV and thermal acceptability ratings every 5 minutes. For comparison, the calculated PMV results using on-site measured parameters were also plotted on the same graph. The temperature fluctuation amplitudes in Condition 3, 4 and 7 ranged between 5 °C to 7 °C (air temperature) and were higher than those in Condition 2, 5 and 6 which were generally around 3–4 °C. Comparing TSV with the calculated PMV, it is evident that the previously mentioned *overshoot* effect (overestimate of warm and cool sensations) commonly occurred in both sudden warming and sudden cooling stages during all DLC events, with that in large temperature cycles (Condition 3, 4 and 7) being especially pronounced. Also, this overshoot was usually stronger during the first cycle, but was attenuated during subsequent cycles. Thermal acceptability votes in Conditions 2, 4 and 5 were almost above 80% throughout the whole DLC event while in Condition 3, 6 and 7, thermal acceptability strayed from 80% limit for different durations. Detailed experimental effects during DLC events will be discussed in the following sections.



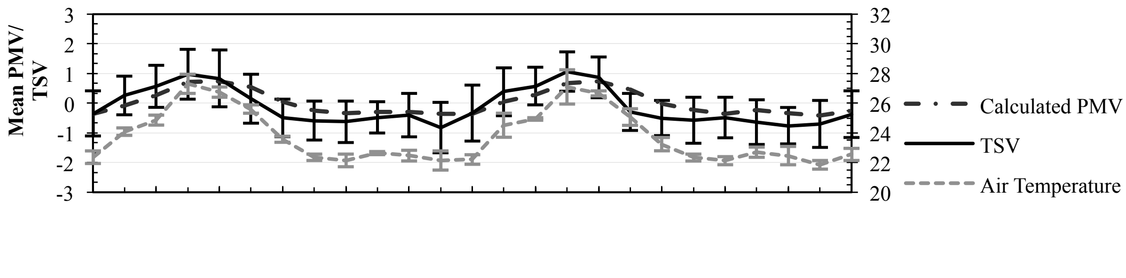
Condition 1

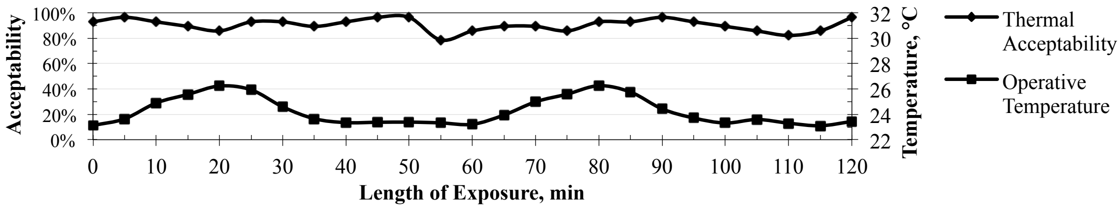


Condition 2

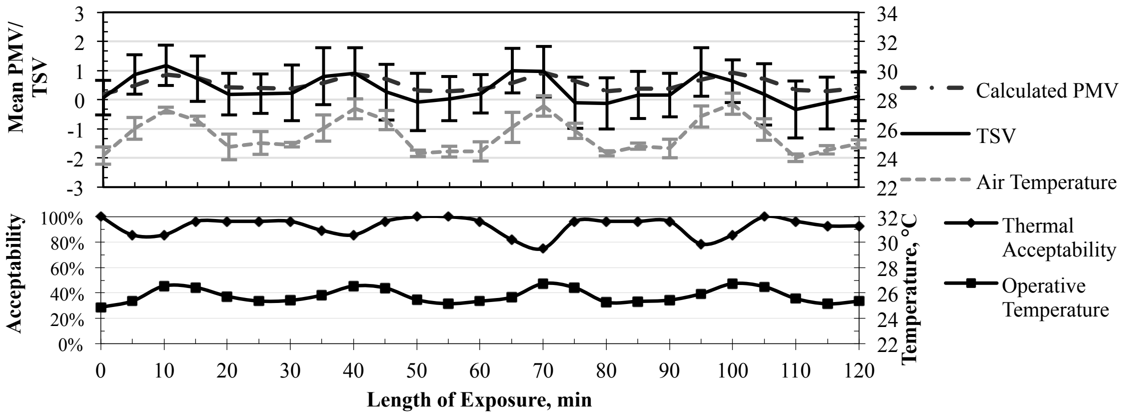


Condition 3

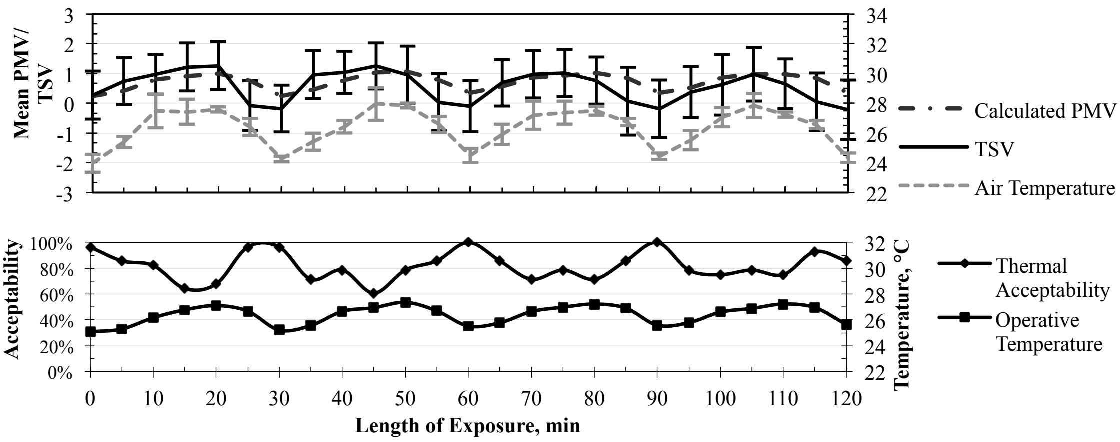




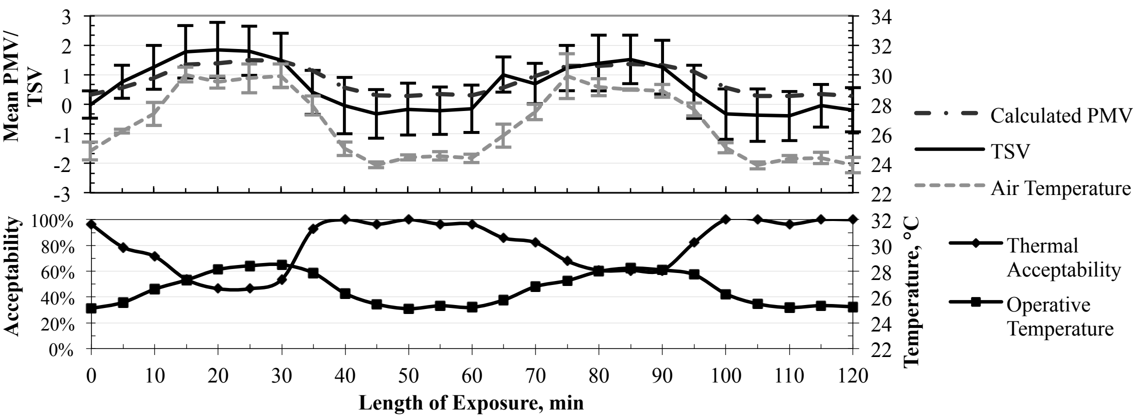
Condition 4



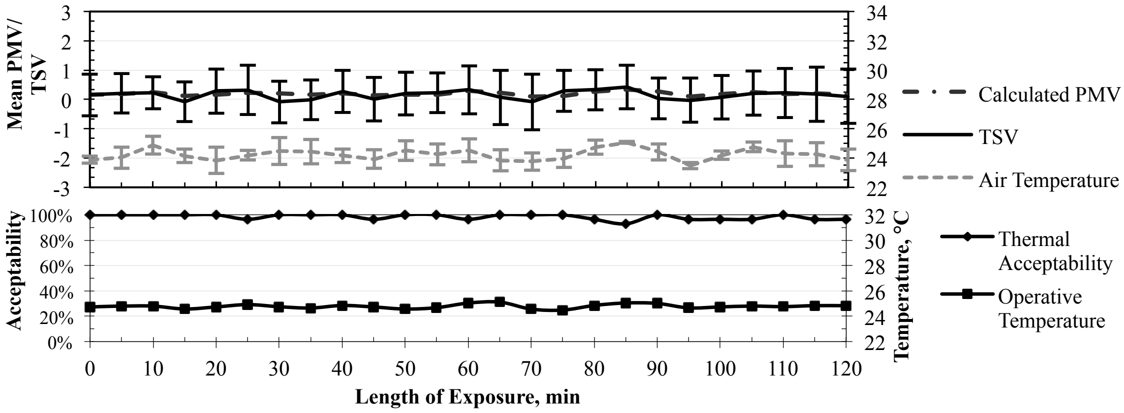
Condition 5



Condition 6



Condition 7



Condition 8

Figure 5-3 Air temperature, operative temperature, calculated PMV, subjects' TSV and thermal acceptability in two experiments (error bars indicate standard deviation)

5.3. Predictors of Thermal Sensation Vote during DLC Events

Steady-state experiments by Rohles (1973) and Rohles and Nevins (1971) on 1600 college-age students revealed correlations between TSV and temperature, humidity, sex, and length of exposure. Air speed was also a significant predictor for subjects' thermal sensation (Fanger, 1972). However, under transient exposures, the rate of skin temperature change has been clearly demonstrated to be related to thermal sensation in thermal transients (Ring and de Dear, 1992; Attia and Engel, 1981; Rohles, 1981). Schellen et al. (2010) reported age difference regarding thermal sensation. The above-mentioned parameters along with experiment condition (Level 2 variable) have been tested in the MLM with possible two-way interactions. The rate of operative temperature change in the ambient environment was adopted instead of the rate of subjects' skin temperature change since the latter was not monitored during the experiments. Although the air speed was not controlled in the experiment, it was expected to vary from heating to cooling stages in the occupied zone. The monitored values showed a variation between nearly negligible values to 0.18 m/s during heating and cooling stages respectively. Thus, air speed was also tested in the MLM and turned out to be a highly significant predictor.

5.3.1. Level 1 main and within-level interaction effects

There are five main significant predictors that have been detected by both of the experiments—operative temperature, vapour pressure, rate of temperature change, length of exposure and air speed. The operative temperature, vapour pressure and rate of temperature change were significantly positively related to TSV, while occupants' length of exposure in the thermal environment and the air speed were significantly negatively related to TSV. Note that the effect of the rate of temperature change on TSV confirms the previously mentioned *overshoot* effect (Ring and de Dear, 1992; Hensel, 1981). It is expressed as either a positive/negative value representing a warm/cold overshoot respectively. In the MLM model, the regression coefficients for the rate of temperature change were 0.020 for Experiment 1 and 0.035 for Experiment 2, meaning that if the other predictors remain the same, the rate of temperature change of ±10 °C/h would cause a warm/cold sensation overshoot of 0.20 for Experiment 1 and 0.35 for Experiment 2.

Apart from the main effects, there were significant interaction effects observed between some main predictors, although these effects were not consistent in both experiments. Significant interaction effect means that main predictors not only affect subjects' thermal sensation independently, but also have a joint impact. Specifically, the relationship between TSV and one main predictor would be modified by different levels of values of other main predictors. For Experiment 1, taking Condition 3 as an example, the relationship between TSV and air speed (the regression coefficient) was significantly modified by the value of the operative temperature. If the operative temperature was higher than the mean value in Experiment 1, the air speed had larger negative impacts on TSV than when the operative temperature was lower than the mean value. Similarly, the relationship between TSV and rate of temperature change was also significantly modified by two other parameters—air speed and subjects' length of exposure. The overshoot of subjects' TSV due to a warm temperature change would be ameliorated by a higher air speed which was above the mean value and longer length of exposure in this environment. On the contrary, if the air speed was lower than the mean value and subjects were just exposed to this warm temperature change, the overshoot effect of TSV would be more pronounced.

Experiment 2 produced more interaction effects between the main predictors than Experiment 1. Taking Condition 6 as an example, the relationship between TSV and operative temperature—known as thermal sensitivity—was significantly modified by subjects' length of exposure in this environment. The longer the exposure, the less thermal sensitivity they had. The relationship between TSV and vapour pressure—humidity sensitivity—was also significantly modified by subjects' length of exposure as well as the operative temperature value. However, subjects' length of exposure had a positive impact on subjects' sensitivity to humidity, meaning that the longer they stayed in a humid environment, the larger the impact of humidity on TSV. The operative temperature also had a positive modification on subjects' sensitivity to humidity, which was strengthened at higher operative temperature. There were also two parameters that significantly modified the relationship between TSV and rate of temperature change: the vapour pressure and length of exposure. The overshoot of subjects' TSV due to a warm temperature change was augmented by higher vapour pressure but attenuated by longer length of exposures.

5.3.2. Condition effects and cross-level interactions

Experiment condition, the Level 2 variable, was tested by MLM along with interactions with Level 1 main predictors for the two experiments and results are shown in Table 5-2. Tests of cross-level interactions revealed that the relationship between TSV and centred operative temperature (thermal sensitivity) significantly varied from experimental conditions in both experiments ($p < 0.05$ for Experiment 1 and $p < 0.001$ for Experiment 2). In Experiment 1, Condition 3 had significantly higher thermal sensitivity (0.170) than Condition 8 ($p < 0.05$), whereas Condition 1, 2 and 8 shared the same thermal sensitivity of 0.058. In Experiment 2, the thermal sensitivity in Condition 7 (0.336) was significantly higher ($p < 0.05$) than the control condition, while Condition 3, 4 and 8 shared the same thermal sensitivity of 0.115. The relationship between TSV and centred vapour pressure / rate of temperature change did not significantly vary from experimental conditions. The interaction effect between centred air speed and experimental condition was significant at $p < 0.05$ in Experiment 2 but not significant in Experiment 1.The regression coefficient for centred air speed was significantly higher ($p < 0.05$) in Condition 5 and 6 (3.940) than in Condition 7 and 8 (1.040). The impact of subjects' exposure period on TSV significantly varied from experimental conditions in Experiment 1 ($p < 0.05$) but not in Experiment 2. Condition 1 and Condition 3 observed the highest negative gradient for exposure period -0.298, while -0.139 for Condition 2 and -0.082 for Condition 4.

Table 5-2 The effect of experiment condition and cross-level interactions on TSV for two experiments

Level 2 predictors and cross-level interactions	Experiment 1	Experiment 2
Experiment condition	$p < 0.05$	NS
Experiment condition × centred operative temperature	$p < 0.05$	$p < 0.001$
Experiment condition × centred vapour pressure	NS	NS
Experiment condition × centred air speed	NS	$p < 0.05$
Experiment condition × length of exposure	$p < 0.01$	NS
Experiment condition × rate of temperature change	NS	NS

(NS—not significant)

5.3.3. Sex and age effects and cross-level interactions

The effects of subjects' sex and age, as well as their interactions with Level 1 main predictors, were also tested by MLM for two experiments and results are presented in Table 5-3. Neither sex nor age had a significant effect on thermal sensation during DLC events; nor did these two factors have significant interactions with Level 1 predictors. The only exceptions were an interaction between sex and rate of temperature change in Experiment 2, and an interaction between age and rate of temperature change in Experiment 1. The regression coefficient of rate of temperature change for a female subject (0.035) was significantly higher than that for a male subject (0.019), meaning that in Experiment 2, female subjects were more sensitive to temperature change than male subjects. In addition, subjects older than the mean age in Experiment 1—25.7 years had significantly lower regression coefficient for the rate of temperature change in the model, meaning that older people were not as sensitive to temperature change as subjects at the mean age.

Table 5-3 The effect of subjects' sex, age and cross-level interactions on TSV for two experiments

Level 3 predictors and cross-level interactions	Experiment 1	Experiment 2
Sex (Female=0, Male =1)	NS	NS
Sex × centred operative temperature	NS	NS
Sex × centred vapour pressure	NS	NS
Sex × centred air speed	NS	NS
Sex × length of exposure	NS	NS
Sex × rate of temperature change	NS	$p < 0.05$
Centred age	NS	NS
Centred age × centred operative temperature	NS	NS
Centred age × centred vapour pressure	NS	NS
Centred age × centred air speed	NS	NS
Centred age × length of exposure	NS	NS
Centred age × rate of temperature change	$p < 0.05$	NS

(NS—not significant)

Figure 5-4 summarizes Level-1 main predictors and observed within-level interaction effects discussed above in two experiments. In order to establish which main predictors or interaction effects (the independent variables) had greater effects on TSV (the dependent variable) in a multilevel multiple regression analysis, standardized regression coefficients which have removed the units of measurement of predictor and outcome variables were calculated for all Level 1 main predictors and interaction effects by applying Equation 5-1 from Hox (2002) and listed in Table 5-4.

$$Standardized\ coefficent = \frac{unstandardized\ coefficient \times Standard\ Deviation\ of\ explanatory\ variable}{Standard\ Deviation\ of\ outcome\ variable}$$

Equation 5-1

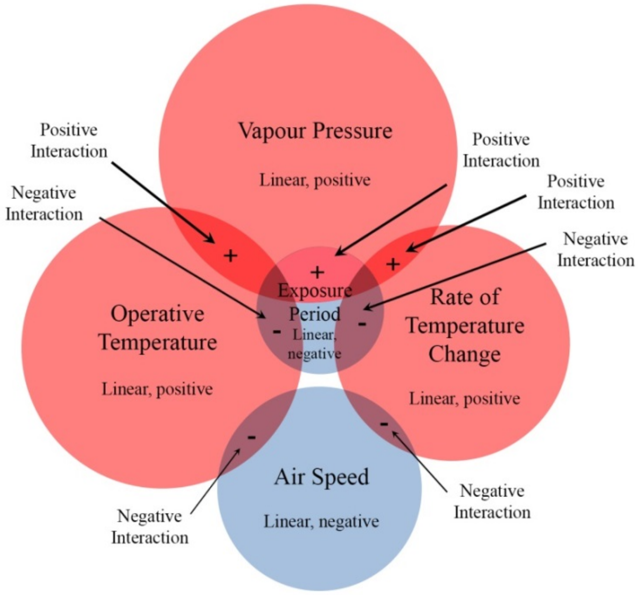


Figure 5-4 Level-1 main predictors and observed within-level interaction effects in two experiments

Table 5-4 Regression coefficients (unstandardized and standardized) for significant Level 1 & 2 predictors / interactions in two experiments

Main predictors	Experiment 1		Experiment 2	
	Unstandardized Coefficients	Standardized Coefficients	Unstandardized Coefficients	Standardized Coefficients
Intercept	0.086 for Condition 1,2,4; 0.360 for Condition 3	—	0.507	—
Centred operative temperature	0.058 for Condition 1,2,4; 0.170 for Condition 3	0.086 for Condition 1,2,4; 0.253 for Condition 3	0.115 for Condition 3,4,8; 0.336 for Condition 7	0.128 for Condition 3,4,8; 0.374 for Condition 7
Centred vapour pressure	1.163	0.360	0.533	0.141
Centred air speed	-1.701	-0.052	-3.940/-1.040	-0.118/-0.031
Length of exposure	-0.298 for Condition 1 and 3; -0.139 for Condition 2; -0.082 for Condition 4	-0.179 for Condition 1 and 3; -0.084 for Condition 2; -0.049 for Condition 4	-0.111	-0.069
Rate of temperature change	0.020	0.177	0.035	0.301
Centred operative temperature × centred air speed	-.861	-0.040	—	—
Centred air speed × rate of temperature change	-.141	-0.038	—	—
Length of exposure × rate of temperature change	-.006	-0.060	-0.006	-0.062
Centred operative temperature × centred vapour pressure	—	—	0.144	0.043
Centred operative temperature × length of exposure	—	—	-0.073	-0.090
Centred vapour pressure × length of exposure	—	—	0.302	0.090

Centred vapour pressure × rate of temperature change	—	—	0.017	0.039

Table 5-4 reveals that for both experiments, operative temperature, vapour pressure and rate of temperature change were generally the most important predictors for thermal sensation during DLC events. In Hensen's extensive transient thermal comfort literature review (Hensen, 1990), he pointed out that four studies on the effect of varying humidity on thermal sensation and thermal comfort (Gonzalez and Gagge, 1973; Nevins et al., 1975; Gonzalez and Berglund, 1979; Stolwijk, 1979) all indicated that the relative humidity range between 20% to 60% did not have an appreciable effect on the thermal comfort of sedentary or slightly active, normally clothed persons, providing the operative temperature was within or near the comfort zone; relative humidity became more important when conditions were warmer and thermoregulation depended more on evaporative heat loss. Obviously during warm and humid temperature cycles induced by DLC events, relative humidity had a bigger impact on thermal sensation, which could be even more pronounced than the temperature effect.

5.4. Predictors of Thermal Acceptability during DLC Events

Previous literature has not directly looked at how thermal acceptability could be predicted from thermal environmental and demographic parameters. In this study, a multilevel logistic regression has been adopted to identify significant predictors for thermal acceptability during DLC events for both experiments. Table 5-5 shows predictors for thermal acceptability in both experiments and odds ratios calculated for significant predictors. In Experiment 1, operative temperature was not a significant predictor for subjects' thermal acceptability vote, whereas the air speed and the interaction between operative temperature and air speed were both highly significant. The odds ratio of air speed implied that holding the operative temperature fixed, thermal acceptability would increase greatly if air speed was higher than the mean value. Similarly, in Experiment 2, there were three significant Level 1 predictors, namely operative temperature, rate of temperature change and air speed. Length of exposure was not significant; however its interaction effect with rate of temperature change was significant. The odds ratio for centred operative temperature indicated that, holding rate of temperature change, centred air speed and length of exposure at fixed values, the odds of voting acceptable would increase if the operative temperature was higher than its mean value 25.9 °C. Similarly, holding the other three parameters fixed, the odds of voting acceptable would go down when the rate of temperature change increases towards the warm direction and go up when the air speed increases from its mean value 0.05 m/s.

Table 5-5 Estimate of predictors for probability of voting acceptable in both experiments

Experiment	Fixed effects	Estimate	Std. Error	z value	Significance	Odds Ratio
Experiment 1	(Intercept)	3.330	0.614	5.425	5.79E-08 ***	27.942
	Centred operative temperature	-0.088	0.191	-0.462	0.644	
	Centred air speed	21.334	8.722	2.446	0.014*	1.84E+09
	Centred operative temperature × Centred air speed	9.955	2.566	3.880	0.0002***	21050.719
Experiment 2	(Intercept)	6.149	0.805	7.636	2.25E-14***	468.151
	Centred operative temperature	-0.847	0.273	-3.100	0.002**	0.429
	Rate of temperature change	-0.128	0.025	-5.022	5.12E-07*	0.880
	Centred air speed	15.786	4.735	3.334	0.001***	7.17E+06
	Length of exposure	-0.303	0.168	-1.804	0.071	
	Rate of temperature change × length of exposure	0.048	0.020	2.397	0.017*	1.049

(***: $p<0.001$; **: $p<0.01$; *: $p<0.05$)

5.5. Overall Acceptability of Tested DLC Events and Limits on Temperature Cycles, Ramps and Drifts

For each subject in each experiment, the proportion of unacceptable votes throughout a DLC event was calculated to represent the proportion of time in a specific condition that this subject felt the thermal environment to be unacceptable (p). This parameter was correlated with subjects' overall acceptability votes in multilevel logistic regression model and was highly significant in predicting overall acceptability in both experiments. Plots of predicted probability of overall acceptability for both experiments were shown in Figure 5-5. In order to guarantee a 90% overall acceptability of DLC events, the proportion of time that the thermal environment is deemed unacceptable should not exceed 35%, according to Figure 5-5. Applying this criterion to the judgement of overall acceptability for 6 DLC conditions based on the thermal acceptability plots in Figure 5-3, Condition 2, 4 and 5 were clearly acceptable while Condition 3 was borderline.

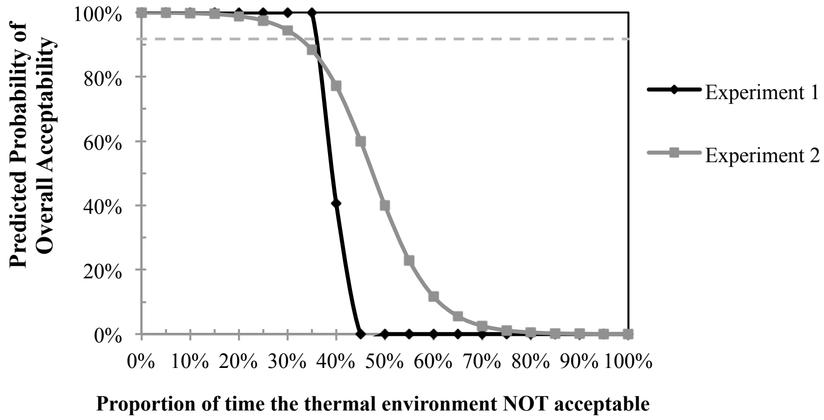


Figure 5-5 Predicted probability of subjects' overall acceptability of DLC events against proportion of time the thermal environment is deemed unacceptable

Based on the normative 80% thermal acceptability criteria, the permissible maximum operative temperature change from the adapting temperature can be figured out for each DLC condition from Figure 5-3. Table 5-6 shows the maximum operative temperature allowed derived from the two experiments in this study, specifically from Condition 2, 4 and 5. It should be noted that these limits are also dependent on the adapting temperature and its location in the steady-state comfort zone. For example, in Experiment 1, the adapting temperature (operative temperature 23.2 °C) was below the neutral temperature (operative temperature 24.5 °C) whereas in Experiment 2, the adapting temperature (operative temperature 24.9 °C) was around the neutral temperature. Consequently, subjects in Experiment 2 tolerated smaller amplitudes of operative temperature than in Experiment 1 (shown in thermal acceptability plot in Figure 5-3). Comparing with ASHRAE 55 (2013) limits for temperature cycles, ramps and drifts (Table 2-4), the temperature fluctuation amplitudes in all DLC events tested in this study went far beyond (Table 5-6). On this evidence, it is reasonable to conclude that the

ASHRAE limits are overly conservative with temperature fluctuations in that not one of the tested DLC events complied with the ASHRAE standards, yet half of them yielded high thermal acceptability.

Table 5-6 The permissible maximum operative temperature change (°C) based on 80% thermal acceptability criteria derived from the current study compared with ASHRAE 55 (2013) (values in the brackets indicate the corresponding limits depicted by ASHRAE 55-2013)

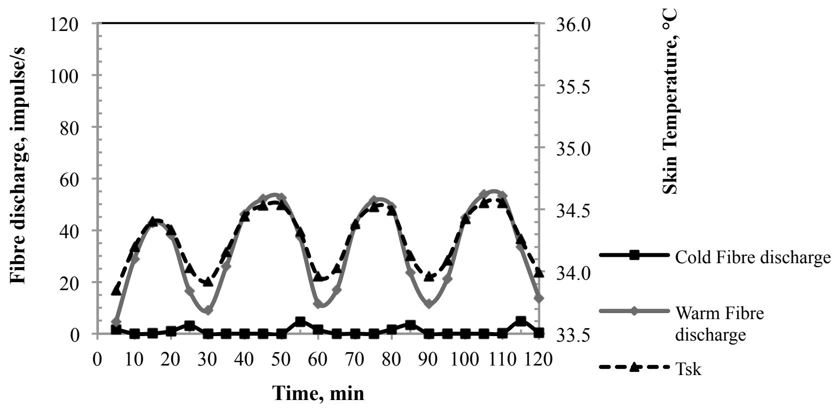
Experiment	Adapting temperature, °C	Time period, h		
		0.2	0.25	0.5
1	23.2	1.8	2.2 (1.1)	3.3 (1.7)
2	24.9	1.7	—	—

5.6. Discussions

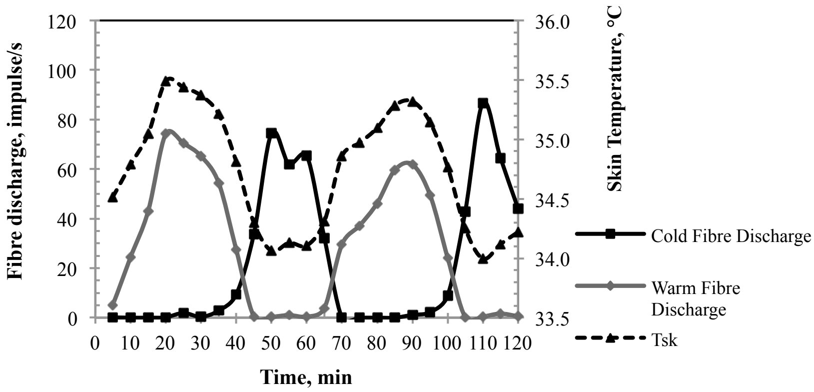
5.6.1. Thermal sensitivity and numerical model simulations

As mentioned in Table 5-2, there is a consistent conditional effect (difference) observed in both experiments—subjects' thermal sensitivity in two large temperature cycles (Condition 3 in Experiment 1 and Condition 7 in Experiment 2) was uniformly higher than in smaller temperature cycles or control conditions. Since previous literature implies that thermal sensitivity might be related to rate of temperature change during temperature ramps and drifts (although no consistent result obtained), in this study, the relationship between thermal sensitivity and rate of temperature change was further tested for each experiment condition in both experiments by adding a three-way interaction item in MLM. Results show that in Experiment 1, only Condition 4 detected a significant relationship ($p < 0.01$) between thermal sensitivity and rate of temperature change, while in Experiment 2, both Condition 6 and 7 detected significant relationships ($p < 0.001$ for both Conditions). For all three conditions, thermal sensitivity had a positive linear relationship with rate of temperature change, meaning that subjects have higher sensitivity when temperature is changing faster. Taking the range of temperature variations into account for the above conditions, it seems that there is a threshold of temperature amplitudes within which there is no significant difference in subjects' thermal sensitivity. When temperature variation exceeds this threshold, thermal sensitivity increases when temperature changes faster. From the results of this study, the threshold is estimated to be 3–4 °C (air temperature).

Based on the general properties of cutaneous thermoreceptors, Ring and de Dear (1991) and de Dear et al. (1993) developed a model based on heat diffusion through the skin for the dynamic response of cutaneous thermoreceptors to temperature stimuli at the skin surface. In this study, the model was used to simulate thermoreceptor impulse frequency during a typical large temperature cycle (Condition 7) and a typical small temperature cycle (Condition 2). Figure 5-6 graphs the numerically simulated warm and cold fibre discharge along with the skin temperature for a theoretical subject using measured physical parameters during DLC events. There is larger volume of thermoafferent traffic in the large temperature cycle than in the small one, meaning that in the large temperature cycle the central nervous system receives more neural signals carrying thermal information. Hence, the skin simulation results corroborate with the previous finding that subjects' thermal sensitivity was higher in large temperature cycles than in small ones.



Condition 2



Condition 7

Figure 5-6 Simulated warm and cold fibre discharge and the skin temperature for Condition 2 and 7

The purpose of ASHRAE limits on temperature cycles, ramps and drifts is to prevent occupants from experiencing discomfort due to fast temperature change, especially to avoid sensation overshoot/ shock resulting from the activation of dynamic thermoreceptor response. However, these limits seemed overly conservative when compared with the numerical model simulation results in this study. Although not displayed in Figure 5-6, skin simulation results revealed that for even the largest temperature cycles, the warm and cold fibre discharge still predominantly derived from the static (steady-state) response, while the dynamic sensitivity of thermoreceptors remained dormant for most of the time. As Parkinson and de Dear (2014) have clearly pointed out, the ASHRAE limits for cycles, ramps and drifts remain inconsistent with literature on the role of elevated air movement in extending the upper range of the adaptive thermal comfort zone (Bauman et al., 1998; Hoyt et al., 2009; Tanabe and Kimura, 1994).

5.6.2. Validity of the PMV/PPD model

Previous research literature gives inconsistent conclusions regarding thermal comfort zones during temperature transients. In the current experiments, the percentage dissatisfied calculated from the binary thermal acceptability vote was plotted against TSV using the pooled data from both experiments (Figure 5-7). A best-fit 3rd degree polynomial equation derived from the data was also drawn in Figure 5-7. In order to compare with previous literature that adopted Fanger's criteria for dissatisfaction (subjects whose TSV is beyond ±1.5 defined as dissatisfied with the environment), a probit analysis was carried out to predict percentage of cold dissatisfied and percentage of warm dissatisfied, and then they were combined into the total percentage dissatisfied (shown in Figure 5-7). Fanger's PMV/PPD model is also shown in Figure 5-7 for purposes of comparison.

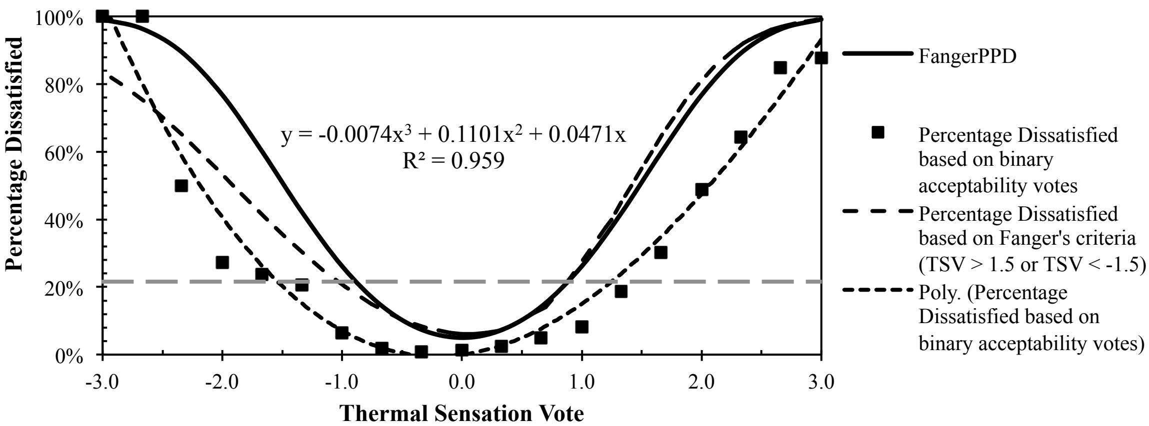


Figure 5-7 The relationship between TSV and percentage dissatisfied based on binary thermal acceptability votes, Fanger's criteria (TSV >1.5 or TSV < -1.5) and the PMV/PPD model

Fanger's PMV/PPD model failed to predict thermal acceptability in the current experiments since it consistently underestimated subjects' acceptability during DLC events. The thermal comfort (80% thermal acceptability) boundaries based on the binary acceptability votes spanned between TSV range of [-1.5, 1.2], which was much wider than the [-0.85, 0.85] range defined by the PMV/PPD model. Also, instead of a symmetric comfort zone around a neutral PMV, the comfort zone developed from binary acceptability votes in the current experiment was displaced to the cooler side (the magnitude of -1.5 is larger than 1.2), meaning that subjects were more tolerant of cooler temperatures than warmer ones. The percentage dissatisfied based on Fanger's criteria demonstrated close agreement with PPD curve in the warm side (+0.85 for 20%

dissatisfaction), however in the cooler side, it defined a wider comfort zone than the PPD curve (-0.97 for 20% dissatisfaction). Comparing two criteria defining the thermal comfort zone, a binary thermal acceptability vote leads to a wider comfort range than the one derived from TSV values. As pointed out by Hensen (1990), different acceptability criteria explain the contradictory results in the literature; yet in this study, thermal comfort zone during DLC events was wider than predicted by the PMV/PPD model regardless of the acceptability criteria adopted.

5.6.3. Thermal comfort zones during temperature cycles

Previous literature has also demonstrated a link between thermal comfort zones during temperature variations and the rate of temperature change, although the exact relationship remains controversial (Sprague and McNall, 1970; Wyon et al., 1971; Wyon et al., 1973; Nevins et al., 1975; Rohles et al., 1980; Kolarik et al., 2009). In this study, data from two experiments were pooled together and the upper and lower temperature limits of 80% thermal acceptability were determined for variant rates of temperature change bins of 5 °C/h interval (Figure 5-8). Due to limited range of temperatures tested for each bin, the solid arrow beside the bars indicate that the 80% thermal acceptability limits might go beyond the temperature limits indicated in Figure 5-8. There appears to be a bifurcation of thermal comfort zones with the cooling transients being associated with wider comfort zones than their warming counterparts. During the warming temperature transients away from subjects' neutral temperature, the width of comfort zone tends to decrease when the rate of temperature change is higher. This trend can also be observed from Figure 5-3 where in two large temperature cycles with relatively higher rate of temperature change (Condition 3 and 7), thermal acceptability drops below 80% at lower temperatures than in smaller cycles with the same adapting temperature. In contrast, during the cooling temperature transients towards the neutral temperature, the comfort zone has been extended towards the warm side. As demonstrated in Figure 5-3, there are sudden spikes in thermal acceptability at the initiation of cooling stages in Condition 3, 6 and 7 even if the operative temperature is still 27–28 °C. Relating to the alliesthesia theory, this scenario can be understood as an instance of positive spatial alliesthesia (Parkinson and de Dear, 2014): after being exposed to an upward temperature ramp away from neutral temperature for some time, subjects perceived the sudden convective cooling that was superimposed on warmer-than-neutral temperatures as pleasurable and highly acceptable, because the cooling supply air falling on their heads, necks effectively offset or countered the thermoregulatory load-error of the warm ambient conditions.

Regarding the impacts of rate of temperature change on the width of comfort zones during cold transients, unfortunately, no strong conclusion could be derived from Figure 5-8 due to lack of adequate data for faster cold transients. However, if related to the previous study by de Dear et al. (1993), the conclusion could still be drawn that faster cold transients lead to reduced thermal comfort zone. In effect, de Dear et al. (1993) has observed conscious thermal sensations approximately twice as sensitive to ambient temperature down-steps as they are to equal magnitude of up-step transients, meaning that subjects have experienced substantial cold sensation overshoot leading to thermal discomfort. However, this higher intensity of cold overshoot is not discernable from Figure 5-3 in this study mainly because the rate of temperature change in temperature cycles was much slower than in step-changes. Consequently, it would be reasonable to conclude that thermal comfort zone shrinks during faster thermal transients regardless of the direction of temperature change, which is consistent with Hensel’s summary of the transient thermal comfort literature (1981).

The extended comfort zone during cooling transients shown in Figure 5-8 also reveals an opportunity for non-steady-state indoor thermal environments to achieve the occupant thermal acceptability higher than 80% with adequate local stimulus to offset the load-error—that is, to exploit the phenomenon of alliesthesia. In that case, not only the building energy impacts on the environments could be ameliorated, but also building occupants’ sensory function could be activated and energized which overcomes thermal boredom.

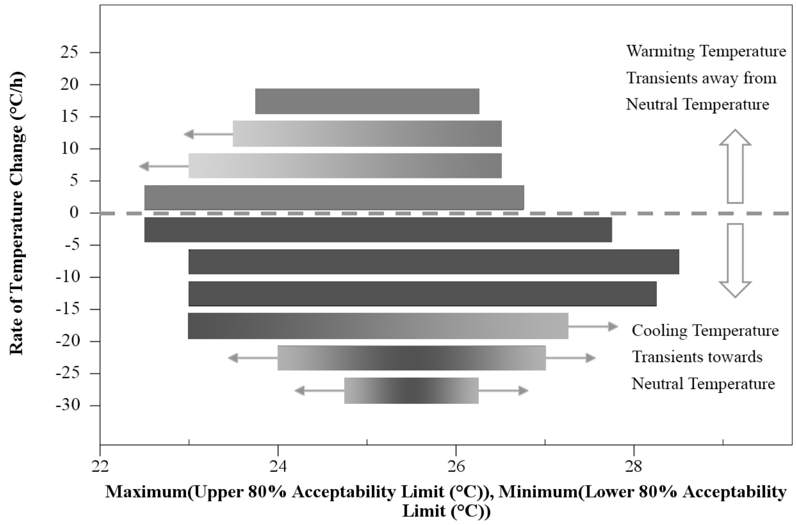


Figure 5-8 Breakdown of 80% thermal acceptability temperature limits for variant rates of temperature change

5.7. CONCLUSIONS

This chapter has explored university students' thermal sensation and thermal acceptability during various DLC events. The following conclusions can be drawn:

- Comparison with TSV and PMV indicates overshoot effects in both sudden warming and sudden cooling stages during DLC events. Out of 6 DLC conditions tested, 3 of them were clearly accepted by subjects.
- During DLC events, operative temperature, vapour pressure, rate of temperature change, length of exposure, air speed, along with several interaction effects significantly predicted subjects' thermal sensation, among which operative temperature, vapour pressure and rate of temperature change were the most important predictors for both experiments. Thermal sensitivity in two large temperature cycles (Condition 3 and 7) was significantly higher than that in small temperature cycles or the control condition. Subjects' sex and age generally did not significantly affect TSV.
- In Experiment 1, air speed and its interaction with operative temperature significantly predicted subjects' thermal acceptability; in Experiment 2, air speed, operative temperature, the rate of temperature change as well as its interaction

with subjects' length of exposure all significantly predicted subjects' thermal acceptability.

- Results from current experiments imply that limits on temperature cycles, ramps and drifts defined in ASHRAE 55 (2013) are overly conservative since all DLC conditions tested in the experiment went far beyond the standard's limits but still they yielded high levels of thermal acceptability; also, the numerical simulation of thermoreceptors revealed that the dynamic sensitivity of thermoreceptors remained dormant for most of the time during DLC events.
- No matter which acceptability/ dissatisfaction criteria were adopted, the thermal comfort zone of our sample during DLC events was wider than predicted by the PMV/PPD model on the cooler side. The thermal comfort zone shrinks when the temperature changes faster regardless of direction of change. Results from this study imply a possibility of achieving 80% thermal acceptability in non-steady-state thermal environment with application of local stimulus—in effect, alliesthesia.

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

In this chapter, 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. This chapter aims to investigate how DLC-induced temperature fluctuations affect university students' cognitive performance; it 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.

6.1. Cognitive Performance Test Results Compared with Previous Studies and Tests of Sequence Effects

The mean and standard deviation of 8 cognitive performance tests in both experiments were listed in Table 6-1 and compared with corresponding general benchmark results reported in Hampshire et al. (2012) based on all users of the CBS website. Table 6-1 showed that mean scores of 7 tests in the current experiments were higher than Hampshire et al.'s (2012) broader benchmarks, whereas the mean score for *Hampshire Tree* was lower. Since participants for the current experiments were well-educated university students, mean scores, generally, were expected to be higher than those for the much larger and more diverse sample of CBS website users, as reported in Hampshire et al. (2012). Standard deviations obtained in this study were similar to the broader benchmarks.

Table 6-1 Comparison of mean and standard deviation for 8 cognitive performance tests obtained by the current experiments compared to the broader benchmark scores reported by Hampshire et al. (2012)

Cognitive performance tests	Current experiment, n=56		Hampshire *et al.,* 2012, n=44,600	
	Mean	Standard deviation	Mean	Standard deviation

1. *Digit Span*	8.54	1.87	7.22	1.52
2. *Rotations*	127.00	42.54	88.72	36.32
3. *Odd One Out*	12.81	2.66	10.43	3.31
4. *Spatial Search*	8.50	2.03	8.23	2.10
5. *Spatial Span*	6.38	0.97	6.15	1.07
6. *Feature Match*	146.15	35.00	131.35	32.79
7. *Grammatical Reasoning*	18.72	5.35	17.38	5.01
8. *Hampshire Tree*	46.89	17.81	64.00	10.19

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.

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 Table 6-2 and Table 6-3. 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.

Table 6-2 Tests of sequence effects on cognitive performance in Experiment 1

Cognitive performance test	Sequence effects of experimental weeks	Sequence effects within an experimental session
1.*Digit Span*	2.68^{**}	0.30
2.*Rotations*	8.60^{***}	8.17^{*}
3.*Odd One Out*	2.26	1.53
4.*Spatial Search*	0.87	-2.03
5.*Spatial Span*	-0.14	1.32
6.*Feature Match*	2.88^{**}	0.77
7.*Grammatical Reasoning*	3.58^{**}	2.46
8.*Hampshire Tree*	1st order 36.12^{***}, 2nd order -4.78^{**}	8.99^{**}
Overall cognitive performance	1st order 9.05^{***}, 2nd order -1.13^{**}	0.08

($^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$)

Table 6-3 Tests of sequence effects on cognitive performance in Experiment 2

Cognitive performance test	Sequence effects of experimental weeks	Sequence effects within an experimental session
1.*Digit Span*	1.32^{*}	1.35
2.*Rotations*	10.11^{***}	0.08
3.*Odd One Out*	4.19^{***}	1.00
4.*Spatial Search*	1.10	-1.64
5.*Spatial Span*	0.71	0.30
6.*Feature Match*	0.61	-0.17
7.*Grammatical Reasoning*	7.81^{***}	5.34^{**}
8.*Hampshire Tree*	1st order 38.03^{***}, 2nd order -4.91^{**}	4.59
Overall cognitive performance	1st order 10.94^{***}, 2nd order -1.34^{**}	0.26^{*}

($^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$)

6.2. Effects of Experimental Conditions on Cognitive Performance

6.2.1. 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 6-4.

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 Figure 6-1 and Figure 6-2). 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. Figure 6-3 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 6-4 Effects of different experimental conditions on cognitive performance tests in two experiments (NS—Not significant)

Cognitive performance test	Experiment 1	Experiment 2
1.*Digit Span*	$p < 0.05$	NS
2.*Rotations*	$p < 0.05$	NS
3.*Odd One Out*	NS	NS
4.*Spatial Search*	NS	NS
5.*Spatial Span*	NS	NS
6.*Feature Match*	NS	NS
7.*Grammatical Reasoning*	NS	NS
8.*Hampshire Tree*	NS	$p < 0.01$
Overall cognitive performance	$p < 0.05$	NS

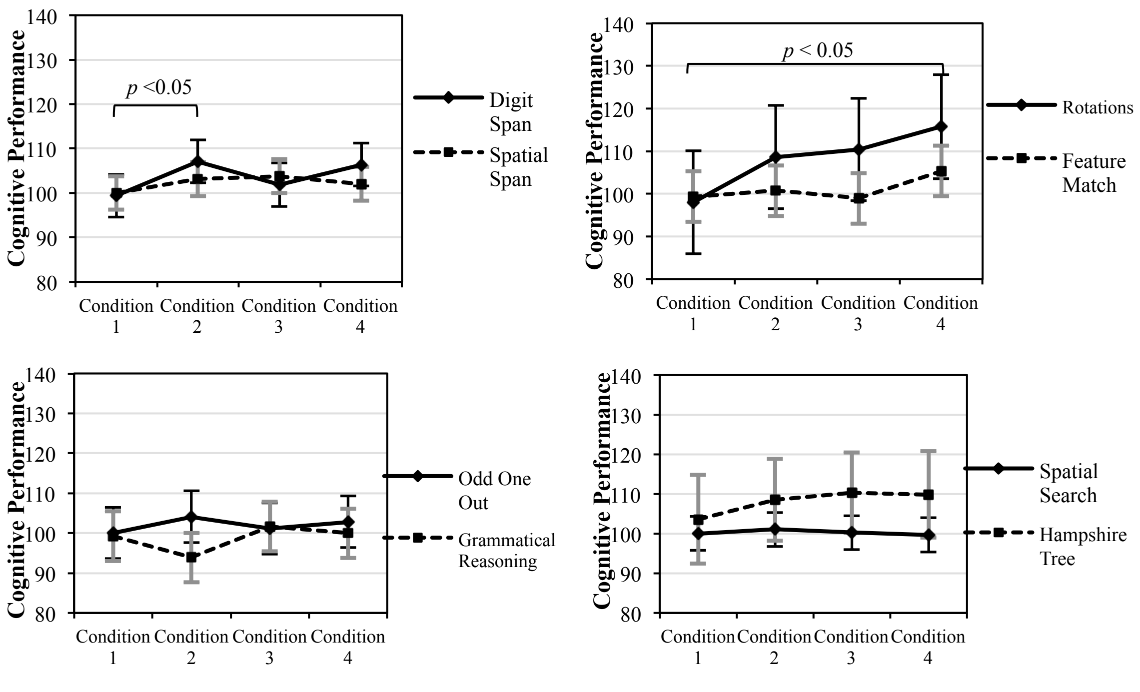


Figure 6-1 Estimated marginal means of 8 cognitive performance tests with 95% CI in Experiment 1 after adjustment for significant sequence effects

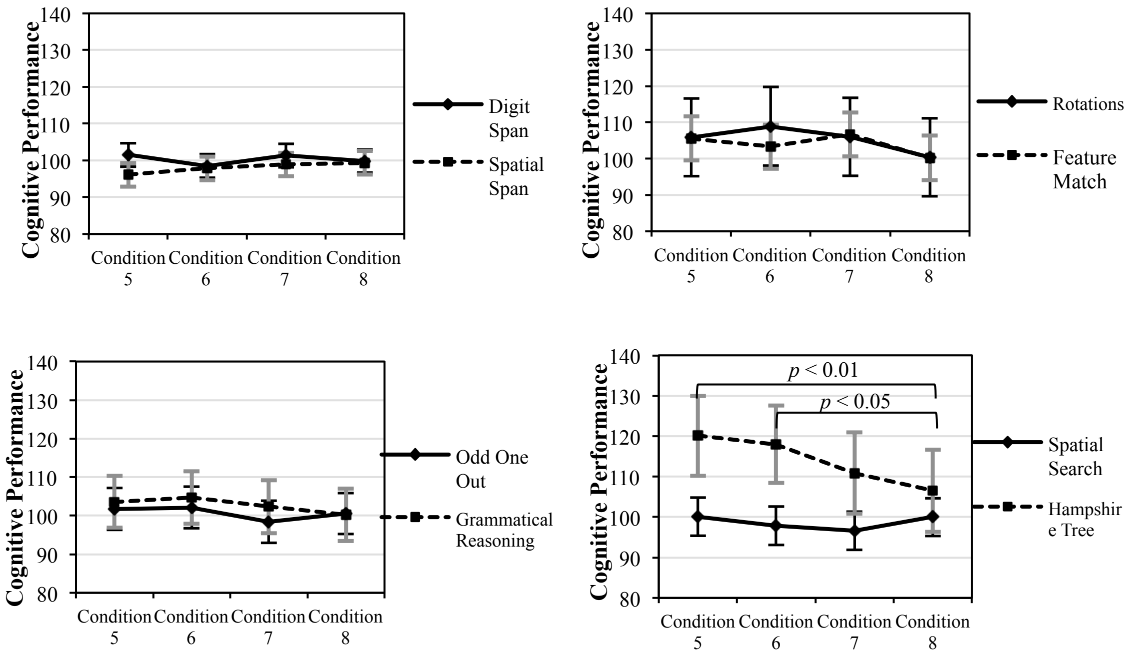


Figure 6-2 Estimated marginal means of 8 cognitive performance tests with 95% CI in Experiment 2 after adjustment for significant sequence effects

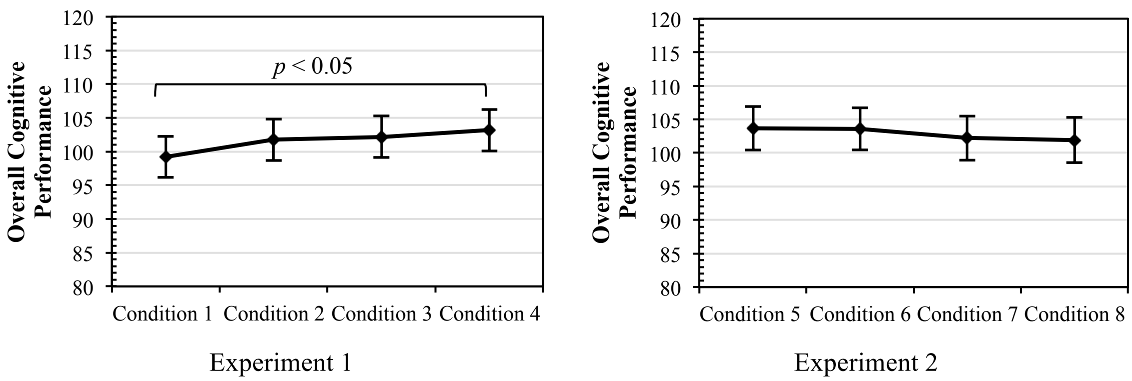


Figure 6-3 Estimated marginal means of overall cognitive performance with 95% CI in two Experiments after adjustment of significant sequence effects

6.2.2. Between-subject comparisons

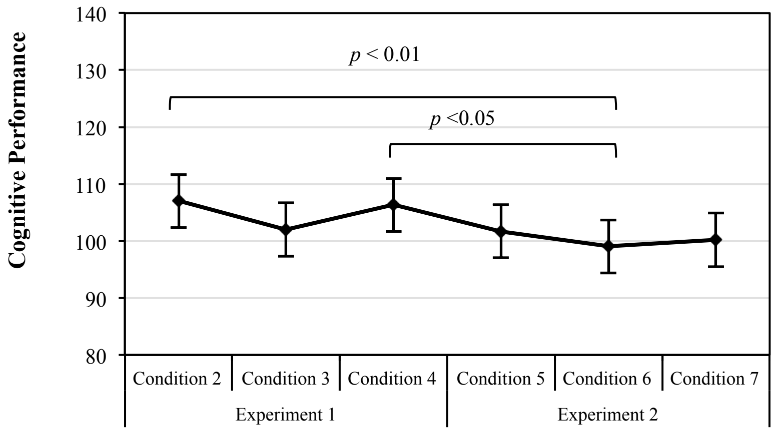
The experimental design of this study does not permit valid comparison of cognitive performance between the two control conditions—Condition 1 at a steady 22 °C and Condition 8 at a steady 24 °C—for the reason that subjects' interindividual differences in cognitive performance are quite likely to be 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 6-5. The two sequence effects—learning and fatigue—were also tested.

Table 6-5 Between-subject comparisons of different DLC conditions (only significant comparisons were included)

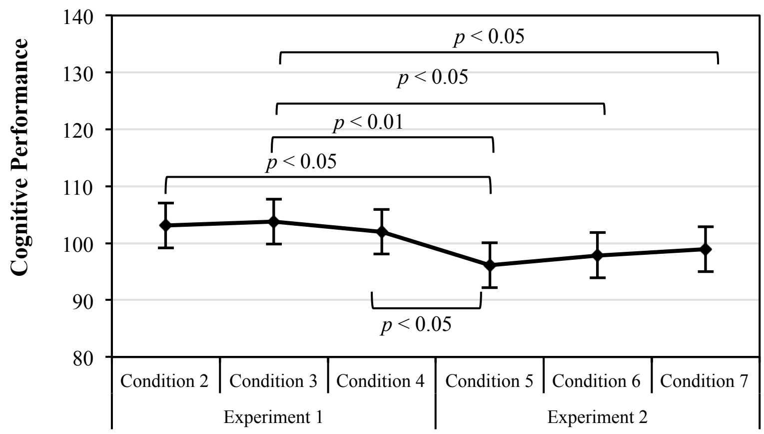
(R) Reference group	(E) Experiment-2 groups	Sequence effects of experimental weeks	Sequence effects within an experimental session	Significant performance tests	Mean difference (E - R)	Significance
Condition 2	Condition 5	NS	NS	*Spatial Span*	-7.00	$p < 0.05$
	Condition 6	NS	NS	*Digit Span*	-8.57	$p < 0.01$
Condition 3	Condition 5	$p < 0.05$	NS	*Spatial Span*	-7.62	$p < 0.01$
	Condition 6	$p < 0.05$	NS	*Spatial Span*	-5.61	$p < 0.05$
	Condition 7	$p < 0.05$	NS	*Spatial Span*	-5.64	$p < 0.05$
Condition 4	Condition 5	NS	NS	*Spatial Span*	-5.93	$p < 0.05$
	Condition 6	$p < 0.05$	NS	*Digit Span*	-7.24	$p < 0.05$

(NS—Not significant)

For the majority of cognitive tests, performance scores under the various DLC 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 6-5, 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 Figure 6-4). 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).



Digit Span



Spatial Span

Figure 6-4 Estimated marginal means with 95% CI of the *Digit Span* and the *Spatial Span* cognitive tests

6.3. Effects of Different Cycling Stages on Participants' Four Cognitive Skills

As discussed in Chapter 3.4.5, 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 6-6 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 6-6 Cognitive skills with significant score differences observed between different stages of DLC-induced temperature cycles

Conditions	Sequence effects of experimental sessions	Sequence effects within experimental session	Cognitive skills tested	Mean difference (Cycling on – Cycling off)	Significance
Condition 2	NS	NS	Reasoning	-10.20	$p < 0.05$
Condition 3	$p < 0.05$	NS	Memory	-5.40	$p < 0.05$
Condition 5	$p < 0.001$	NS	Planning	13.07	$p < 0.05$
Condition 6	1st order $p < 0.01$; 2nd order $p < 0.05$	NS	Planning	13.09	$p < 0.01$
Condition 7	$p < 0.05$	NS	Planning	10.78	$p < 0.05$

(NS—Not significant)

6.4. 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, it 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.

6.4.1. 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 6-7 and Table 6-8 for Experiments 1 and 2 respectively.

Table 6-7 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

Cognitive skills tested	Sequence effects of experimental sessions	Sequence effects within experimental session	TSV	TSV^2	TSV^3	c-Ta	$c\text{-}Ta^2$	$c\text{-}Ta^3$	Rate of temperature change	Thermal acceptability
Memory	0.94	0.23	0.64	-1.01	0.13	0.72[a]	-0.16	0.10	-0.004	3.70

Concentration	4.37***	0.60	0.04	-0.03	-0.02	1.13	0.16	0.04	0.26*	4.90
Reasoning	2.68**	0.36	0.89	-0.59	-0.002	0.52	0.06	0.01	0.12	5.15
Planning	1st order 18.68***; 2nd order -2.64**	1st order -10.95*; 2nd order 2.48*	1.85	0.22	0.60*	0.02	-0.07	-0.01	-0.11	-4.16

(^{a} $0.05 < p < 0.08$; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$)

Table 6-8 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

Cognitive skills tested	Sequence effects of experimental sessions	Sequence effects within experimental session	TSV	TSV^2	TSV^3	c-Ta	c-Ta^2	c-Ta^3	Rate of temperature change	Thermal acceptability
Memory	0.89*	-0.16	1.01	0.11	0.15	0.52	0.28	0.05	0.08	-0.39
Concentration	1st order 19.81**; 2nd order -2.95*	0.17	1.34	-0.10	0.10	1.03^{a}	0.29	0.06	0.09	3.38
Reasoning	5.93***	1.56*	0.33	-1.05*	0.51	-0.58	-0.31^{a}	-0.07*	-0.09	4.67^{a}
Planning	1st order 15.77**; 2nd order -2.81**	2.48**	-5.19***	1.54	0.22	-3.15***	0.65*	-0.10	-0.54***	11.52**

(^{a} $0.05 < p < 0.08$; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$)

In the cooler of the two experiments—Experiment 1 (Table 6-7), 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 6-8), 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-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.

6.4.2. Relationship between overall cognitive performance and thermal comfort indexes

In previously published literature on thermal effects on performance (Seppänen and Fisk, 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 6-9.

Table 6-9 Quantitative relationship of overall cognitive performance index with TSV, centred air temperature, rate of temperature change and thermal acceptability in two experiments

Experiments	Sequence effects of experimental sessions	Sequence effects within experimental session	Interaction effect	TSV	TSV^2	TSV^3	c-Ta	c-Ta^2	c-Ta^3	Rate of temperature change	Thermal acceptability
Experiment 1	1st order 9.05^{***}, 2nd order -1.13^{*}	0.08	—	0.64	-0.45	0.14	0.32	-0.02	-0.001	0.11^{*}	2.61
Experiment 2	1st order 8.95^{***}, 2nd order -1.34^{**}	-0.32	0.23^{*}	-0.49	-0.73^{*}	0.10	-0.22	0.09	0.003	-0.05	5.03^{**}

($^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$)

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.

6.5. Discussion

6.5.1. 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 setpoint 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 that 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.

6.5.2. 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 that 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 6-7 and Table 6-8—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 (Figure 6-5). 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 6-7 to Table 6-9. 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).

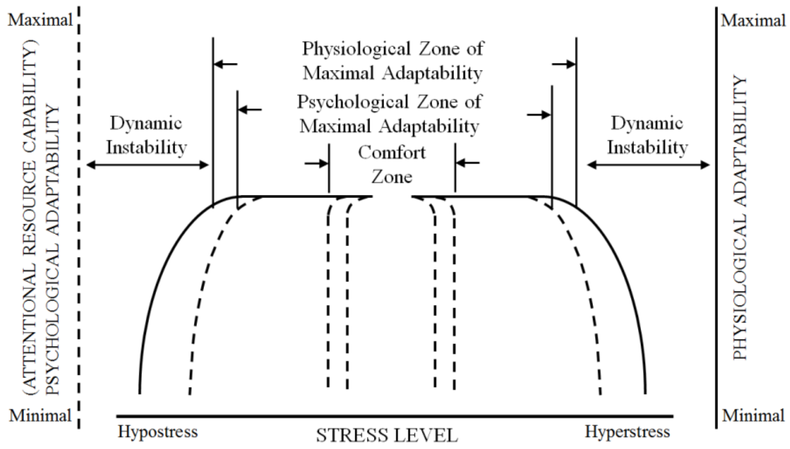


Figure 6-5 The extended-U model between stress and performance (Hancock and Warm, 1989; Hancock and Ganey, 2003)

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.

6.6. CONCLUSIONS

This chapter 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.

7. CONCLUSIONS

Along with global warming and growing number of heatwave days in Australia, there is increasing *peak demand* in the national electricity market, driven primarily by air-conditioning. Instead of building more network capacity to meet the peak demand, initiatives to curtail or shift peak load have gained momentum in many countries in recent years. *Demand response* is such a strategy that provides an opportunity for consumers to play a significant role in the operation of the electric grid by reducing or shifting their electricity demand during peak periods in response to time-based tariffs or other financial incentives. 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 penalty tariffs 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 may occur for just a few hours in a year.

Direct load control (DLC) is a utility-sponsored demand response program that allows a utility to cycle specific appliances on and off during peak demand periods such as heatwaves. In exchange, participating customers are entitled to financial incentives or discounted electricity bills. Direct load control of air-conditioners typically consists of duty cycle restrictions and thermostat setback. Under a duty cycle restriction program, the air-conditioner compressor is cycled on and off at predetermined intervals with the fan on even if the setpoint temperature is not met.

DLC programs have been widely carried out in utility companies in USA, but in Australia, they are still at the early stage of development. Previous DLC programs (studies) have been focused on residential buildings and small business buildings. There have been no DLC studies in university lecture theatre settings. In addition, previous DLC studies have mostly been focused on peak load savings; few of them have considered thermal comfort impacts, not to mention a "right-here-right-now" survey that enables correlation between subjects' thermal comfort/cognitive performance and DLC-induced thermal environmental parameters. Previous laboratory studies on thermal comfort during temperature cycles, ramps and drifts have yielded many contradictory results; in spite of these studies, there has been no study to date looking directly at the thermal comfort impacts of temperature cycles induced by direct load control strategies. As for cognitive performance studies, although there are numerous research papers on the effects of thermal environment or thermal stress on cognitive performance, only a handful of studies have been conducted under 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.

This study explored the effects of various DLC air-conditioning strategies, in particular duty cycle restriction approach, on university students' thermal comfort and cognitive performance. Modes of inquiry included computer simulation of DLC-induced thermal environments, and climate chamber experiments with human subjects to replicate these simulated DLC events. Simulation methods were used to set up building and system models in order to simulate indoor thermal environments of a typical university lecture theatre induced by DLC events composed of various algorithms. By applying the *orthogonal array* method, eight DLC algorithms were selected from 48 simulation cases for purposes of the human subject experiments to test subjects' thermal comfort and cognitive performance under these simulated DLC events in a controlled climate chamber. Multilevel linear modeling was used to analyse the experimental data.

Chapter 4 presented the results from the matrix of 48 parametric simulations of the DLC-induced thermal environments in a typical university lecture theatre. DesignBuilder and EnergyPlus were used to simulate thermal environments inside a typical Australian university lecture theatre during DLC events under various off cycle fractions (duration of AC compressor being off during an activation period), cycling periods (time for a complete cycle), cooling setpoint temperatures, building envelope thermal performance specifications and ventilation rates. Results indicate that the off cycle fraction, cycling period and cooling setpoint temperature all had relatively large influences on occupant comfort compared to the building envelope's thermal performance and ventilation rate. The analysis explored thermal comfort impacts by applying the PMV/PPD index to simulated indoor climates. Although most of the simulation cases exceeded the permissible thermal comfort range defined by Fanger's predicted mean vote (PMV) / predicted percentage dissatisfied (PPD) method, since the applicability of the PMV/PPD method in transient thermal environments is questionable, the *actual* comfort impacts of DLC events must be examined in either laboratory experiments or field studies with human subjects. In order to maintain acceptable thermal comfort for occupants, DLC algorithms must be applied judiciously and customized to the specific building. University buildings with poor envelope thermal performance and high ventilation rate should adopt conservative DLC scenarios, while buildings with good envelope thermal performance and moderate ventilation rate can implement more radical DLC algorithms to achieve higher peak demand reduction. All else being equal, DLC algorithms with shorter cycling periods have less adverse thermal comfort impacts than the longer ones.

Chapter 5 presented the experimental results on the effects of DLC-induced temperature cycles on university students' thermal sensation and thermal acceptability. In two separate climate chamber experiments, 56 subjects' thermal comfort responses were closely monitored during six DLC conditions and two control conditions simulated in a climate chamber. Results showed that the *overshoot* effect (overestimate of warm and cool sensations) occurred in both sudden warming and sudden cooling phases during all DLC events. Nevertheless, half of the DLC conditions were clearly accepted by subjects. Multilevel linear modelling of thermal sensation demonstrates that operative temperature, vapour pressure and the rate of temperature change were the three most important predictors during DLC events. Multilevel logistic regression indicated that in DLC conditions with lower adapting temperatures, thermal acceptability was significantly predicted by air speed and its interaction with operative temperature whereas in DLC conditions with higher adapting temperatures, by air speed, operative temperature and the rate of temperature change. No matter which acceptability/ dissatisfaction criteria were adopted, subjects' thermal comfort zone during DLC events was observed to be wider than predicted by Fanger's PMV/PPD model, i.e. the subjects were more tolerant of cooler temperatures. Thermal comfort analysis also suggested that ASHRAE 55-2013 was overly conservative in its specification of limits for temperature cycles, ramps and drifts.

Chapter 6 presented the experimental results for subjects' cognitive performance during DLC-induced temperature cycles in the climate chamber. 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. The majority of cognitive performance tests have examined significant learning effects, thus results needed to be adjusted before treatment effects could be thoroughly explored. Both within-subject and between-subject comparisons confirmed that DLC-induced temperature cycles in either the cooler or warmer experiment generally did not significantly affect participants' scores on eight cognitive performance tests, with a few exceptions. Tests of relationship between cognitive performance and thermal comfort indexes yielded distinct results between two experiments: in Experiment 1 with a cooling setpoint 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 DLC temperature cycles; in Experiment 2 with a cooling setpoint of 24 ºC, subjects' reasoning and planning performance observed a trend of decline at the higher heat intensity and longer heat exposure. The current experimental results confirmed that simpler cognitive tasks were less susceptible to temperature effects than more complex tasks; the effect of thermal variations on cognitive performance followed an extended-U relationship with performance being relatively stable across a range of temperatures.

The current research findings have profound practical implications for building management practices. It is widely accepted practice in commercial buildings that the cooling and heating setpoint should be constrained within a very narrow temperature range (deadband) in the mistaken belief that temperature fluctuations are associated with discomfort and performance decrement for occupants. The widespread over-cooling of large centrally air-conditioned buildings during summer in Australia, South East Asia and North America incurs excessive and unnecessary energy use, greenhouse gas emissions and financial expense, resulting in tremendous peak loads during heat-wave days. However, results from this experimental study suggest that, as long as the DLC algorithms are judiciously designed and tailored for specific building physics and occupant conditions, it is highly probable that DLC events will be well accepted by building occupants without incurring substantial thermal discomfort. They can even enjoy a positive spatial alliesthesia and relief from “thermal boredom”.

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 encourage application of demand response strategies such as direct load control to reduce peak electricity demands without substantively impacting productivity.

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Appendix A: Paper 1

Zhang, F., & de Dear, R. (2015). Thermal environments and thermal comfort impacts of Direct Load Control air-conditioning strategies in university lecture theatres. *Energy and Buildings*, 86 (0), 233–242.

Statement of Co-Author Contribution

Fan Zhang: As a lead author, Fan Zhang was responsible for the entire process of drafting the manuscript, including literature review, conduct of simulation and analysis, and development of discussion and conclusion.

Richard de Dear: Discussed initial project design and concept. He assisted Fan Zhang with the discussions. The manuscript was reviewed and edited by Richard de Dear.

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Thermal environments and thermal comfort impacts of Direct Load Control air-conditioning strategies in university lecture theatres

Fan Zhang*, Richard de Dear

Indoor Environmental Quality Laboratory, Faculty of Architecture, Design and Planning, The University of Sydney, Room 589, Wilkinson Building G04, Sydney 2006, NSW Australia

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ABSTRACT

As a common approach to manage peak electricity demands associated with air-conditioning (AC), the Direct Load Control (DLC) strategy has yielded positive results in residential and small commercial buildings in countries that include USA, Australia and Canada. However, in educational settings with high occupant density and ventilation requirements, thermal comfort impacts of DLC remain unclear. EnergyPlus was used to simulate thermal environments inside a typical Australian university lecture theatre during DLC events under various cycling schemes, cooling set-point temperatures, building envelope thermal performance specifications and ventilation rates. The analysis explores thermal comfort impacts by applying the PMV/PPD index to simulated indoor climates. Results indicate that off cycle fraction (duration of AC compressor being off during an activation period), cycling period (time for a complete cycle) and cooling set-point temperature have relatively large influences on occupant comfort compared to the building envelope's thermal performance and ventilation rate. In order to maintain acceptable thermal comfort for occupants, DLC algorithms must be applied judiciously and customized to the specific building. All else being equal, DLC algorithms with shorter cycling periods have less adverse thermal comfort impacts than the longer ones.

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1. Introduction

As large institutional consumers universities are adversely impacted by peak electricity loads. To meet the peak demand, universities in Australia are levied substantial penalty rates. According to the network price list of a large utility company in Sydney Australia, institutional customers with a load no less than 750 MW h per annum will automatically be charged the kVA Demand[1] Time-of-Use Tariff (US $9.44/kVA in 2012). Many Australian universities have exceeded the 750 MW h annual consumption thresholds and in Sydney the kVA Demand Time-of-Use Tariff is applied to the highest 30-min peak demand in the preceding 12 months. Peak demand events may only occur for a few hours in a year, but this kVA Demand Time-of-Use can represent up to 20% of the institution's total electricity costs for a whole year.

The Direct Load Control (DLC) strategy represents one of the most common approaches to managing peak electricity demand. In DLC programs, an electricity utility or aggregator has the facility to remotely shut down or cycle high-demand electrical equipment (air-conditioners, water heaters, pool pumps, etc). This paper only discusses DLC of air-conditioners (AC). Typical DLC AC control approaches include duty cycle restriction and temperature setback [2]. Duty cycle restriction involves cycling the AC compressor on and off at predetermined intervals. Under this program, the thermostat setting is maintained, but the AC compressor is only allowed to run for a predetermined time even if the set-point is not met, and then switched off (with the fan on) for a fixed period. Off cycle fraction refers to the amount of time the AC compressor will be off during an activation period. Cycling period is the time for one complete cycle of AC compressor on and off. By synchronizing and coordinating duty cycles across a large number of their customers, the utility company or the aggregator can effect substantial load shedding during peak events.

Many utility companies in USA, Australia, and Canada have conducted trials on DLC AC duty cycle restriction in residential and small business buildings in recent years (shown in Table 1).

* Corresponding author. Tel.:+61 2 9351 5914; fax: +61 2 9351 3031.
E-mail address: fzha6386@uni.sydney.edu.au (F. Zhang).

[1] Demand is a measure of the maximum amount of electricity being drawn from the grid over a half-hour interval. It may be measured in units of kVA or kW. Demand charges from the utility are typically levied on the customers' maximum demand for a particular time period. Depending on the network tariff, demand charges may be split into time of use periods. Furthermore, demand may be measured in rolling periods, e.g. highest demand for the last 12 months [1].

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Table 1
Representative DLC programs or trials in recent years.

DLC programmes or trials	Country	Year	Customer segment addressed	Off cycle fractions	Cycling periods	DLC event duration	Customer feedback on comfort	References
ETSA Utilities Residential Direct Load Control Trial	Australia	2005–2008	Residential	25%, 50%	0.5 h, 1 h	1 – 3 h	No customer complaints	[3]
PG & E's SmartAC Program	USA	2007	Residential and small business	50%	0.5 h	Up to 6 h	9% discomfort	[4]
BGE Demand-Response Infrastructure Pilot	USA	2007	Residential	30%, 50%, 75%	0.5 h	4 – 5 h	"Comfort issues due to cycling were not a major concern"	[5]
2010 Hydro Ottawa Peaksaver® Program	Canada	2010	Residential and small business	30%, 50%	Not stated	Up to 4 h	12% – 17% discomfort	[6]
Perth Solar City Air-conditioning Trial	Australia	2010–2012	Residential	33%, 50%	0.5 h	Up to 4 h	76% of participants felt "no change" in comfort levels	[7]

Generally speaking, these programs have reported positive results in reducing peak demands without prompting excessive complaints from customers. However to replicate the success of DLC in university lecture theatres two factors must be taken into consideration before any realistic assessments can be made. First, the occupant densities (internal loads) in a lecture theatre are much higher than in a residence. Second, the high occupant density in lecture theatres requires much higher ventilation rates. Classrooms commonly have approximately 15 times greater ventilation volumes (outdoor airflow rate per floor area) than residences [8]. The hot and frequently humid outdoor air that triggered the peak demand event in the first place will be continually introduced into the lecture theatre even when the AC compressor is cycled off, which may compromise occupants' thermal comfort during DLC events.

Indoor thermal environmental conditions during a DLC event depend on many factors including off cycle fraction (the amount of time the AC compressor is off during an activation period), cycling period (time for a complete cycle), cooling set-point temperature, building envelope thermal performance, ventilation rate and so on. By setting up a building and system model in building thermal simulation software, thermal environments during a DLC event can be predicted. In the literature, many building simulation studies address building energy consumption, energy conservation measures and occupant comforts in various built environments [9–13]. In relation to DLC, the extensive recent studies have mainly focused on aggregated load modelling, control strategies and prediction of demand savings [14–18]; no studies concentrating on the thermal environments and thermal comfort during DLC events have been published to date.

Peak load reduction and maintenance of comfort are two important goals for DLC programs, and DLC scenarios should be evaluated from both perspectives. However, at a micro level (single building or customer), the peak load reduction is not readily discernible due to the "rebound effect" [14,19] which refers to the even higher peak load often occurring immediately after the load shedding period. But at a macro level (utility companies or the aggregators), a large number of participating customers with staggered DLC events for sub-groups of customers can still achieve substantial peak load reduction over and above the rebound of sub-groups. This paper does not address demand saving aspects of DLC scenarios, but rather focuses on the thermal comfort impacts on occupants at the single-building scale. It aims to present results of simulated thermal environments within a typical university lecture theatre during DLC events, as induced by various off cycle fractions, cycling periods, cooling set-point temperatures, building envelope thermal performance and ventilation rates.

2. Methodology

DesignBuilder (Version 3.2, released in May 2013), and EnergyPlus (Version 8.0.0.008, released in April 2013), were used in this simulation study. DesignBuilder was used to set up the building geometry and HVAC system configuration; EnergyPlus was then used to set up DLC control schemes and implement the simulation.

2.1. Test Building and System description

2.1.1. Building

The building under study is located in a university campus in Sydney, Australia. This two-level building has a total floor area of 2230 m^2, comprising four lecture theatres, one tutorial room, one canteen, two offices and some other auxiliary spaces. Fig. 1 illustrates the simplified Level 2 plan of the test building. The eastern and western entrances on Level 2 are the main entrances to the building. All four lecture theatres have identical dimensions: 18.8 m length × 15.7 m width × 8.4 m height. They can be accessed either from the back doors located on Level 2 or the front doors located on Level 1 foyer. There are no external windows in this building except glass gliding doors on both Level 2 entrances and the pyramid roof skylight at the centre of Level 2 foyer. The building is normally open from 7 am to 6 pm on weekdays during semester time, though it can be extended to 9 pm or on Saturdays, depending on lecture theatre bookings. During non-semester time, lecture theatres are closed but the building common areas are open from 8 am to 4 pm.

2.1.2. HVAC systems

The building was built in 1970 with a 200 kW natural gas boiler heating system serving four lecture theatres and the foyer areas.

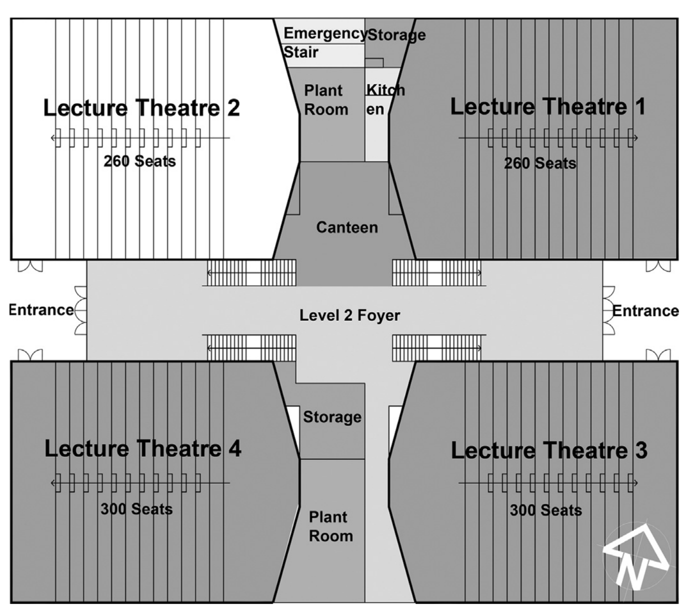

Fig. 1. Simplified Level 2 plan of the test building.

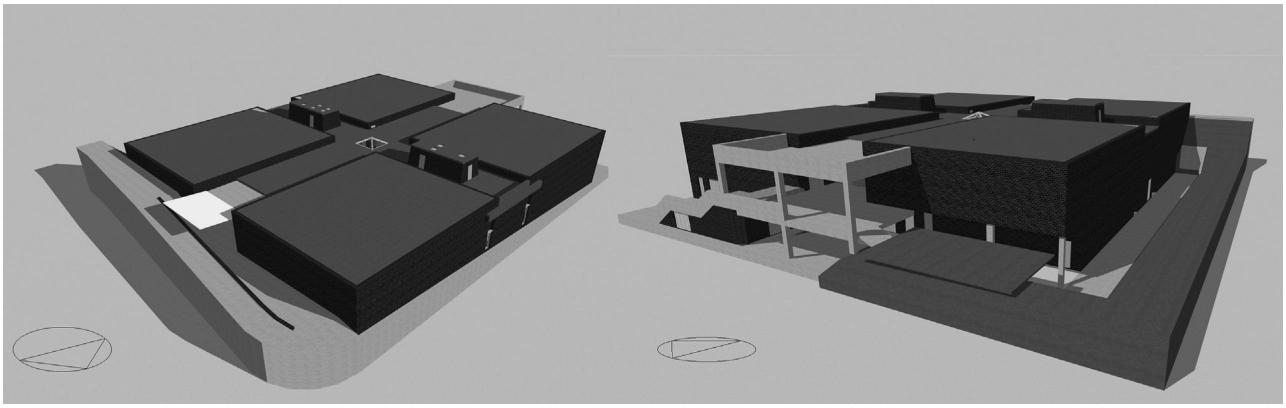

Fig. 2. DesignBuilder model of the test building.

The chilled-water system was installed around 1980. Chilled water is supplied at 6.1 °C by a packaged reciprocating chiller set and a chilled water pump, piped to four conditioners located in level 2 plant rooms. Each conditioner, comprising two cooling coils, has a cooling capacity of 123 kW and serves a single lecture theatre. Condenser water is supplied at 29.4 °C to the chiller from a forced draught cooling tower via a condenser water pump. The chiller has a cooling capacity of 300.7 kW and COP of 3.89. It was selected based on a design where two theatres are occupied simultaneously. Chilled water cooling coils operating between 6.1 and 12.8 °C provide all cooling throughout the building. The design air flow rate for each lecture theatre is 4.72 m^3/s and the cooling supply air temperature is 13.3 °C. The control system activates either chiller or boiler, depending on a central timer and thermostat. The cooling set-point temperature is 22 °C and the heating set-point is 20 °C. Bad practice as they may seem, these set-points are very common in Australia. Capacity control for cooling and heating output is implemented by varying the chilled or hot water flow rate using 3-way modulating control valves while fixed fan speed delivers a constant air flow rate. The tutorial room and the canteen each have their own Direct Expansion (DX) split system. Both Level 1 and Level 2 foyers are naturally ventilated.

2.1.3. Simulation model

The rendered geometry outline of the test building generated in DesignBuilder is shown in Fig. 2. Investigations have been carried out in the test building to obtain actual internal load information, especially the occupancy schedule for model validation purposes. Though only two theatres were designed to be occupied simultaneously, observation revealed that four theatres could hold students at the same time; however the normal occupancy for each theatre was only 60–140 students. Table 2 lists internal load inputs for main spaces in the test building. For HVAC system models, the compound components of fans, cooling coils, heating coils and outdoor air mixers were represented by a four-pipe fan-coil unit in each lecture theatre in DesignBuilder model. The DX systems in the tutorial room and canteen were represented by packaged terminal heat pumps with electric heating coils scheduled “off” at all times. The infiltration rate for the whole building was set to 1 ac/h. The ventilation control mode in Level 1 and Level 2 Foyer was set to “constant” natural ventilation through the building opening schedule.

2.1.4. Weather data for simulation

The test building is in Climate Zone 5 in Australia—a warm and temperate climate [20]. Although hourly based TMY2 or WYEC2 weather files from EnergyPlus were available, a nearby automatic weather station [21] provides 15-min interval real-time weather data, offering a finer resolution than the interpolated hourly weather data. Therefore, a “real day” was selected as the typical DLC event day. In preparing the EnergyPlus Weather (EPW) file, actual observations of dry bulb temperature, dew point temperature, relative humidity, atmospheric pressure, global horizontal radiation, diffuse horizontal radiation, infrared sky radiation, wind speed and wind direction were obtained from the weather station. Direct normal radiation was calculated using the following algorithms [22]:

$$\text{Direct}_{\text{normal radiation}} = \frac{\text{Direct}_{\text{horizontal radiation}}}{\sin\left(\text{Solar}_{\text{height}}\right)}$$

and

$$\text{Direct}_{\text{horizontal radiation}} = \text{Global}_{\text{horizontal radiation}} - \text{Diffuse}_{\text{horizontal radiation}}$$

For simulation of DLC events, a five-day 15-min interval EPW file was compiled, containing the DLC event day and four preceding days. A 10-min interval EPW file was also interpolated from

Table 2
Internal loads for major spaces in the test building.

Spaces	Area (m^2)	Conditioned	Maximum occupancy (people/m^2)	Maximum lighting density (W/m^2)	Equipment (W/m^2)
Lecture theaters	288 × 4	Yes, Central AC	1.04 for theatre 3/4; 0.9 for Theatre 1/2	6.9 – 13.4	2.1
Tutorial rooms	56	Yes, Packaged DX	0.63	8.6	2
Foyers	396	No, naturally ventilated	0.05	10.2	8.5
Precinct offices	58	No	0.03	7.8	3
Canteen	55	Yes, Packaged DX	0.21	8.2	15
Kitchen	7	No	0.09	8	25
Toilets	99	No	0.11	5	5.6
Plant Rooms	62	No	0	5	50
Substation, switch room	97	No	0	5	30
Penthouses	40	No	0	2	40
Plinth Rooms	35	No	0	0	30

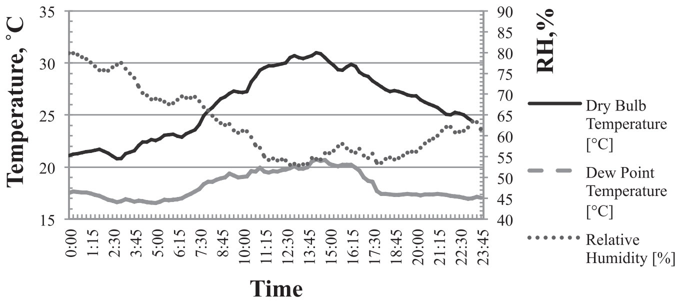

Fig. 3. Dry bulb temperature, dew point temperature and relative humidity on the DLC event day.

the 15-min one to match the needs of different cycling schemes and number of time steps in an hour for the simulation [22]. The selected DLC event day was 22nd March, 2013 based on two considerations: first, investigations in universities in Sydney suggest that the highest electricity peak demand across the whole year typically occurs in March; second, the outdoor dry bulb temperature for a real DLC event is generally above 30 °C. Fig. 3 demonstrates the weather profile on this selected DLC event day.

2.2. Model validation

The "as built" simulation model was validated using available electricity meter readings in two separate periods—July to October, 2012, and March to June, 2013. Real-time weather data for these two periods were employed for validation. Occupancy schedules for the two validation periods were based on theatre booking information and direct observation. In July to October, 2012, the actual consumption was 128.8 MW h compared to 137.3 MW h for simulation, giving an acceptable error of 6.6% according to ASHARE Guideline 14-2002 [23]; in March to June, 2013, the actual consumption was 119.8 MW h and 110.5 MW h for simulation (error 7.7%). The simulated cooling energy consumption for each period was 25.4 MW h and 30.5 MW h, respectively, which takes up 18.5% and 27.6% of the total energy consumption.

2.3. The research design

Five parameters have been identified to have direct influences on indoor thermal environments during DLC events. Other factors such as different HVAC systems and control modes will also have impacts, but are tangential to the research focus of this study. The five parameters and their settings are discussed below.

2.3.1. Off cycle fraction and cycling period

According to previous DLC trials and programmes (e.g. programmes listed in Table 1), 50% off cycle fraction and 0.5 h cycling period are the most commonly used cycling schemes. Other off cycle fractions, such as 25%, 30%, 33%, 65%, 75%, 100% and different cycling periods, such as 1 h have also been used. In this study, three off cycle fractions—33%, 50% and 67%, and two cycling periods—0.5 h and 1 h were selected for simulation.

2.3.2. Cooling set-point temperatures preceding DLC events

Two levels of cooling set-point temperatures were tested, 22 °C and 24 °C. The set-point temperature of 22 °C was based on the actual cooling set-point temperature observed in the test building, whereas 24 °C was derived from PMV by solving the model for zero, which represents theoretical comfort temperature for sedentary occupants dressed in summer clothing.

2.3.3. Building envelope thermal performance

The thermal properties and performance of a building envelope can commonly be represented by two parameters: the overall heat transfer coefficient (*U*-value) and the thermal capacity (thermal mass). *U*-value measures the ability of the building envelope to conduct heat, thus a low *U*-value usually indicates high level of insulation. Thermal capacity measures the ability to store heat. The building envelope with a high thermal capacity is effective in resisting outdoor temperature fluctuation and maintaining relatively constant indoor temperature. Australian university buildings commonly adopt medium to heavy-weight constructions with relatively high thermal capacity, such as concrete, bricks, etc. However, the insulation conditions of these buildings can vary significantly according to the years of construction. For this simulation, two levels of building envelope thermal performance typical for Australia's university building stock were selected. One is the original test building fabric for external walls and roofs, representing the uninsulated 1970′s building with relatively high thermal capacity; the other one is selected from the "Best practice wall, heavyweight" and "Best practice flat roof (no ceiling), heavyweight" in the DesignBuilder building construction database, representing a well-insulated new building with high thermal capacity. Detailed building fabric layers and corresponding *U*-values are listed in Table 3. Thermal properties of the main materials used in the simulation are listed in Table 4. Internal building specifications remain in the "as built" condition across all of the project's simulation scenarios.

2.3.4. Ventilation rates

Two levels of ventilation rates were studied. According to Australian Standard 1668.2–1991 [25], the minimum outdoor airflow rate for classrooms serving students over 16 years of age where an air cleaning unit is not provided is 10 L/s/person. Another level of ventilation rate for simulation was the 50% increase of the minimum level, which is 15 L/s/person.

To summarise, simulation scenarios in this study combined 3 off cycle fractions, 2 cycling periods, 2 cooling set-point temperatures, 2 envelope thermal performance levels and 2 ventilation rates shown in Table 5, yielding 48 simulation cases. Lecture Theatre 2 (highlight in white in Fig. 1) was selected as the test bed of the DLC event simulation since it is located in the north-west of the building, representing a "worst case" scenario in the late Australian summer afternoon. The DLC event lasted for 3 h from 2 pm to 5 pm. It was assumed that Lecture 2 held 130 students; the lighting load was 3 kW and equipment load 0.6 kW. Internal loads and schedules for other lecture theatres or spaces in the building remain the same as in the validation model described above. Direct Load Control was imposed on the original HVAC systems by setting up a cycling schedule to the chilled water loop. Assumptions for thermal comfort simulation are: the clo value for all occupants is 0.5 (0.4 for clothing and 0.1 for chairs). The Metabolic Rate is 1.2 Met for sedentary occupants reading and typing. The indoor air speed is the default value in DesignBuilder–0.137 m/s.

3. Results and discussions

3.1. Thermal environment and comfort during a DLC event

To evaluate the thermal environments during a DLC event, the mean air temperature, zone Mean Radiant Temperature (MRT), zone operative temperature and zone air Relative Humidity (RH) have been plotted from EnergyPlus. The widely used thermal comfort index—Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) have also been plotted to evaluate thermal comfort impacts of the DLC event.

Table 3
Two levels of building envelope fabric and *U*-value for the test building.

Two levels of building envelope thermal performance	Building envelope			
	External walls		Roofs	
	Layers	*U*-value	Layers	*U*-value
Poor building envelope thermal performance	110 mm brick, 100 mm timber stud + 260 mm air space non reflective and unventilated, 10 mm gypsum plasterboard	1.914	10 mm PVC, 40 mm floor/roof Screed, 130 mm concrete reinforced	2.520
Good building envelope thermal performance	105 mm brick, 118.2 mm XPS extruded polystyrene, 100 mm concrete block, 13 mm gypsum plastering	0.251	19 mm asphalt, 13 mm fibreboard, 205 mm XPS extruded polystyrene, 100 mm cast concrete	0.149

Table 4
Thermal properties of main materials used in the simulation.

Material	Thermal conductivity (W/m K)	Density (kg/m^3)	Specific heat J/(kg K)	Volumetric heat capacity J/(m^3 K)
Brick	0.72–0.84	1700–1920	800–840	1.36×10^6–1.61×10^6
Concrete (block, reinforced, cast)	0.51–2.5	1200–2400	1000	1.20×10^6–2.40×10^6
XPS	0.034	35	1400	4.9×10^4
Gypsum Plasterboard	0.25	900	1000	9×10^5
Asphalt	0.7	2100	1000	2.1×10^6

Table 5
Parameters and levels of values for the parametric study.

Levels of parameters	Off cycle fraction (%)	Cycling periods (h)	Cooling set-point temperatures preceding DLC Event (°C)	Building envelope thermal performance levels	Ventilation rates (L/s/person)
Low	33	0.5 h	22	Poor	10
Medium	50	–	–	–	–
High	67	1 h	24	Good	15

Fig. 4 demonstrates thermal environmental parameters for a DLC scenario with 50% off cycle fraction, 0.5 h cycling period, 22 °C cooling set-point temperature, good building envelope thermal performance and ventilation rate 10 L/s/person. Values were plotted every 15 min from 13:30 to 17:30, which was half hour before the DLC event to half hour after it. All four parameters have saw-tooth profiles. Before the event starts, the mean air temperature settled near the cooling set-point temperature 22 °C. When the cooling was off, it drifted to around 26 °C in 15 min, and then came back to about 22 °C when cooling was back on. The MRT was about 2 °C higher than the mean air temperature before the event probably because of direct sunlight being cast on the western walls and roof. During the event, the fluctuation of MRT also lagged behind the mean air temperature for about 15 min and reached around 26 °C at peak. The operative temperature was the average of the mean air temperature and the MRT and ranged from 23 °C to 25.5 °C during the event.

Regarding the RH, it was above 80% when cooling was on and dropped to 67% when cycled off. Although the simulated RH seems to be high in an air-conditioned building, several studies [8,26,27] have provided evidence that high humidity problem is very common in school buildings during hot and humid weather, partly due to the high occupant density which requires high ventilation rates, and partly due to the poor dehumidification capability of commonly used AC systems in schools. According to [8], if there is no latent cooling or internal moisture generation, the room RH would be 85% if the outdoor dewpoint temperature is 21 °C and the room temperature is 24 °C. It also points out that for chilled water AC units with constant volume fan and modulating chilled water valve (the control system in this case), as the cooling load diminishes, the flow of chilled water to the coil is reduced and the coil temperature rises, thus the ability of the coil to remove water vapour from the air declines and eventually disappears (at about 50% load factor). In this case, the chiller is oversized (the calculated cooling load is about 180 kW while the actual cooling capacity of the chiller is 300 kW). Besides, field measurements in October (very dry season in Sydney) have shown that the RH could be higher than 70% when the lecture theatre was populated with about 100 students. Based on above facts, the high humidity in the simulation results seems to be plausible. To ameliorate this situation, commonly adopted methods include the automatic fan-speed adjustment or installing a Dedicated Outdoor Air System (DOAS); both could enhance the dehumidification capability of the HVAC system and maintain lower indoor RH during DLC events.

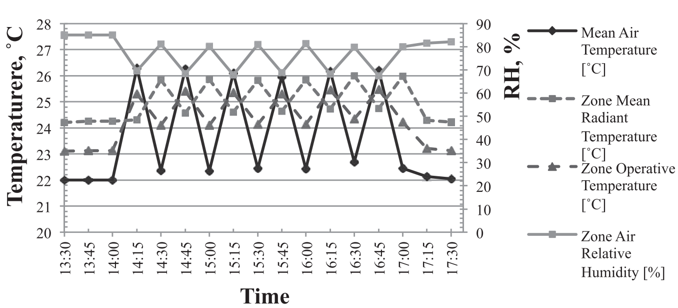

Fig. 4. Thermal environment for 50% off cycle fraction, 0.5 h cycling period, 22 °C cooling set-point temperature, good building envelope thermal performance and ventilation rate 10 L/s/person.

Fig. 5 shows the PMV/PPD index values during the DLC event. Before the event starts, PMV fixed at −0.6, a little below the recommended comfort range of −0.5 to +0.5 by [24]. It indicates that the cooling set-point temperature of 22 °C, the common practice in air-conditioned buildings in Australia, is somehow low for sedentary occupants dressing in typical summer clothing. Along with the temperature rising when the cooling cycles off, PMV increased to around 0.4, still within the comfort range. PPD maintained around 13% when cooling was on and dropped to about 7% when cooling was off, indicating that in this DLC scenario, cycling on and off AC system at 15-min intervals from 22 °C has increased

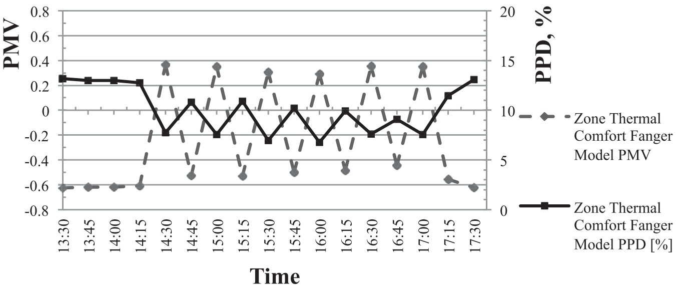

Fig. 5. PMV/PPD for 50% off cycle fraction, 0.5 h cycling period, 22 °C cooling set-point temperature, good building envelope thermal performance, and ventilation rate 10 L/s/person.

occupants' thermal comfort by mitigation of AC overcooling rather than decreasing comfort.

3.2. Effects of different parameters on thermal environments during DLC events

Figs. 6–9 illustrate operative temperature profiles simulated from various parameter values during DLC events. In each figure, two parameters vary while the other three parameters were held constant. Figs. 6–9 demonstrate that all 5 parameters analysed had impacts on occupied zone thermal environments during DLC events. In order to find out which parameter had relatively larger influence, the maximum operative temperatures in all 48 simulation scenarios were analysed in relation to the levels of input parameters in question. One-way ANOVA test revealed that there was a significant difference between impacts of different parameters ($p < 0.001$). *Post hoc* procedure (Games–Howell) [28] was carried out to identify significantly different pairwise comparisons (Table 6). Across the range of parameter values tested which represent typical Australian university lecture theatre settings, the impacts of cycling period variations were significantly larger than impacts of cooling set-point temperature differences and building envelope thermal performance levels, which were in turn significantly greater than impacts of ventilation rate variations. Obviously the magnitude of impacts of various input parameters relates to the range of values tested. All parameters tested covered reasonable and representative ranges for the Australian university sector. Any parameter value outside this range might result in the relative impacts being amplified. In addition, other factors which include HVAC system types, cooling loads and control modes can also be expected to have an impact. To make a general conclusion, in typical Australian university lecture theatres, off cycle fractions, cycling periods and cooling set-point temperatures have relatively larger influences on occupied zone thermal environments during DLC events compared to building envelope thermal performance levels and ventilation rates.

3.3. Thermal comfort impacts of DLC events

Most contemporary thermal comfort standards are specified as an acceptable range of the relevant comfort index. They also

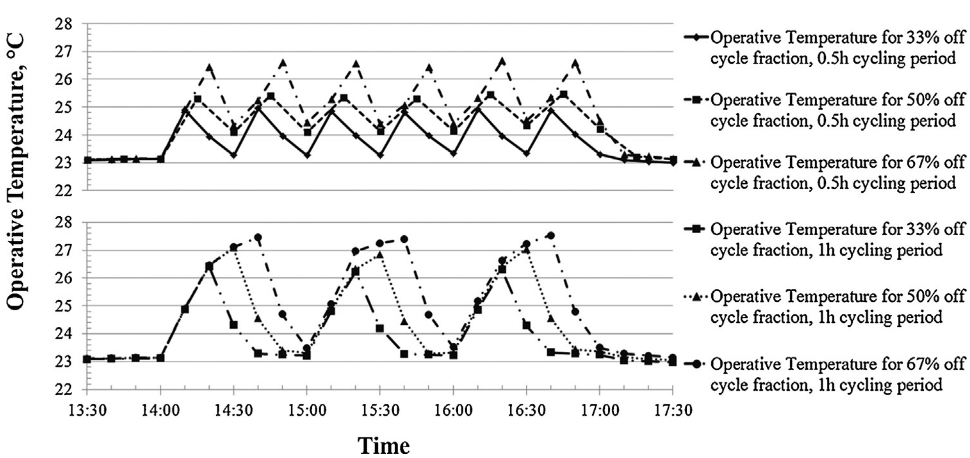

Fig. 6. Operative temperatures for different cycling schemes under 22 °C cooling set-point temperature, good building envelope thermal performance, and ventilation rate 10 L/s/person.

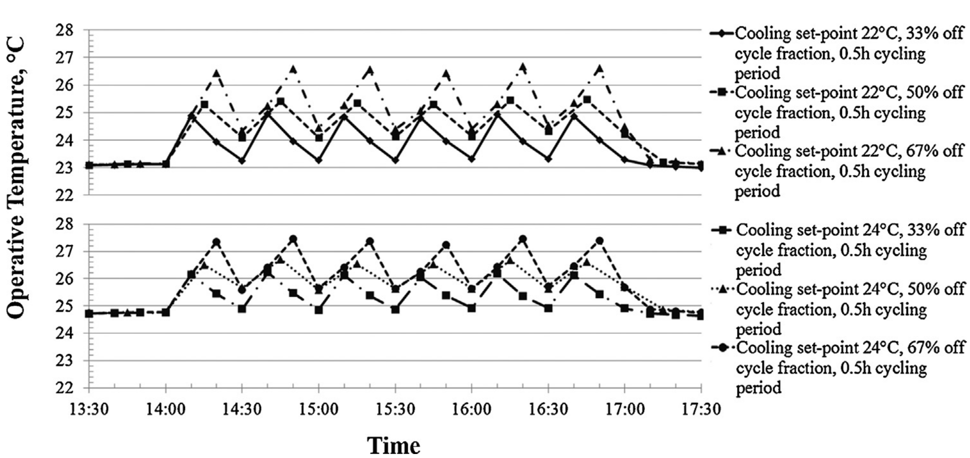

Fig. 7. Operative temperatures for two cooling set-point temperatures under three off cycle fractions with 0.5 h cycling period (good building envelope thermal performance, ventilation rate 10 L/s/person).

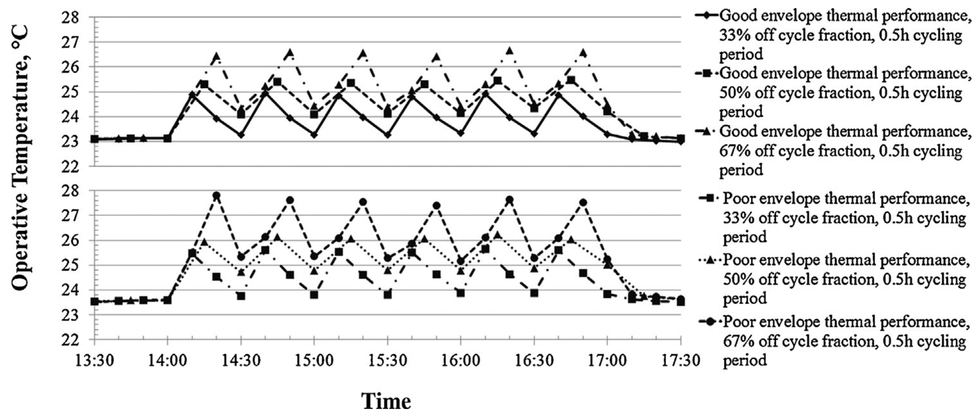

Fig. 8. Operative temperatures for two different building envelope thermal performance levels under three off cycle fractions with 0.5 h cycling period (cooling set-point temperature 22 °C, ventilation rate 10 L/s/person).

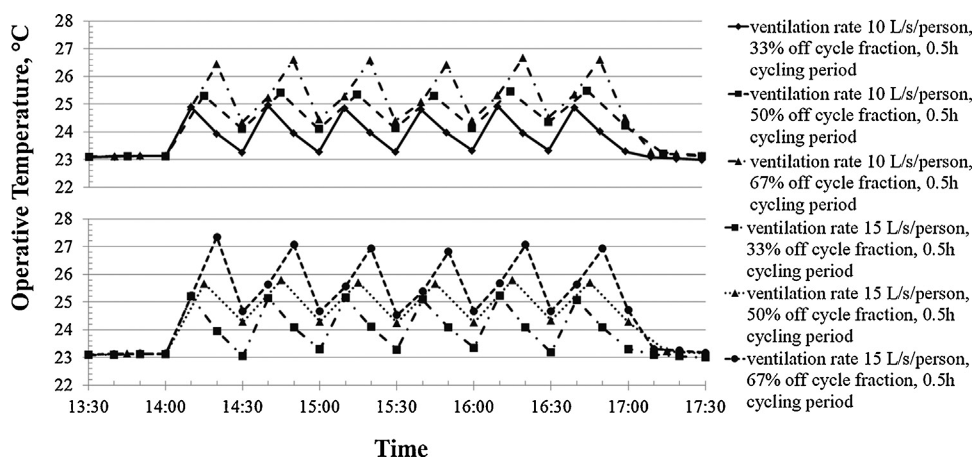

Fig. 9. Operative temperatures for two different ventilation rates under three off cycle fractions with 0.5 h cycling period (cooling set-point temperature 22 °C, good building envelope thermal performance).

stipulate that large temperature fluctuations not under the direct control of individual occupants should be avoided so as to keep thermal environment relatively static. However, above analysis show that duty cycle restriction in a DLC event will cause repeated rises and falls in air temperature, MRT and RH, creating dynamic thermal environments. Since the PMV/PPD model was derived in a controlled climate chamber under steady conditions, it might not be fully appropriate to assess thermal comfort impacts during DLC events, so in this study it serves merely as indicative comfort performance criterion. The actual thermal comfort impacts of DLC events can only be obtained from replicating simulated DLC events within climate chamber experiments with human subjects or in actual field studies.

3.3.1. ASHRAE 55-2013 permissible and simulated temperature changes for temperature drifts

ASHRAE 55-2013 (5.3.5 Temperature Variations with Time) requires that for cyclic variations with a period not greater than 15 min, the maximum allowable peak-to-peak variation in operative temperature is 1.1 °C [24]; for temperature ramps and drifts,

Table 6
Pairwise comparisons of input parameter impacts on the maximum operative temperature during DLC events.

(I) Condition	(J) Condition	Mean difference (I–J, °C)	Sig.
Impacts of off cycle fractions varied between 33% and 67%	Impacts of cycling periods varied between 0.5 h and 1 h	−0.03	1.000
	Impacts of cooling set-point temperatures varied between 22 °C and 24 °C	0.48	0.051
	Impacts of building thermal performance levels varied between good and poor	0.47	0.047*
	Impacts of ventilation rates varied between 10 and 15 L/s/person	0.94	<0.001**
Impacts of cycling periods varied between 0.5 h and 1 h	Impacts of cooling set-point temperatures varied between 22 °C and 24 °C	0.51	0.002**
	Impacts of building thermal performance levels varied between good and poor	0.50	0.001**
	Impacts of ventilation rates varied between 10 and 15 L/s/person	0.97	<0.001**
Impacts of cooling set-point temperatures varied between 22 °C and 24 °C	Impacts of building thermal performance levels varied between good and poor	−0.01	1.000
	Impacts of ventilation rates varied between 10 and 15 L/s/person	0.46	<0.001**
Impacts of building thermal performance levels varied between good and poor	Impacts of ventilation rates varied between 10 and 15 L/s/person	0.47	<0.001**

* $p < 0.05$.
** $p < 0.01$.

Table 7
ASHRAE 55-2013 permissible and simulated temperature changes for temperature drifts [24].

Time period (h)	Maximum operative temperature change allowed in ASHRAE 55-2013 (°C)	Maximum operative temperature change in simulation for 22 °C set-point scenarios (°C)	Maximum operative temperature change in simulation for 24 °C set-point scenarios (°C)
0.2	–	2.2	1.8
0.25	1.1	2.7	2.2
0.5	1.7	5.0	3.9
1	2.2	5.3	4.2

the maximum operative temperature change allowed during a period of time is shown in Table 7. Cyclic variations with a period greater than 15 min are assessed with the ramps or drifts criteria [24]. Since the cycling periods for all DLC events under study are longer than 15 min, they should be treated as temperature drifts and should comply with the requirement in Table 7. Results indicate that simulated operative temperature changes within specific time periods during DLC events all exceeded the ASHRAE 55-2013 limits (see Table 7). Simulation results were grouped according to cooling set-point temperatures. Duty cycle restriction in a DLC event causes temperature fluctuations that exceeded the ASHRAE standard.

3.3.2. PMV/PPD model as the thermal comfort index

As is stated in ASHRAE 55-2013, PMV/PPD is widely used to determine the requirements for thermal comfort in occupied spaces. It recommends that PMV should be held within the range of −0.5 to +0.5 and PPD within 10% [24]. Fig. 10 illustrates a boxplot of maximum PMV/PPD in 48 scenarios pooled by different values of parameters. Across all DLC scenarios, the mean of maximum PMV is 0.9 ± 0.3 (SD). The maximum PMV in only part of the lower quartile values fell below +0.5. Generally speaking, the interquartile range of maximum PMV in parameters with low-level values (such as 33% off cycle fraction, 0.5 h cycling period, good envelope thermal performance, etc.) fell between the PMV range of +0.5–+1, while the upper half of maximum PMV in parameters with high-level values (67% off cycle fraction, 1 h cycling period, poor envelope thermal performance, etc.) all exceeded +1. The mean maximum PPD in 48 scenarios is $26.2\% \pm 10.3\%$ (SD). It should be noted that the maximum PMV and PPD values during DLC events do not necessarily correspond to each other since in some cases such as the one stated in Section 3.1, the maximum PPD was achieved when AC was on and the PMV was very low due to AC overcooling. For this reason, even the lower quartile PPD values exceeded 10% (shown in Fig. 10). Fig. 10 also reveals that most DLC scenarios have exceeded the permissible thermal comfort range by PMV/PPD methods specified in ASHRAE 55-2013.

Though PMV/PPD may not be strictly appropriate for DLC events, previous laboratory studies on temperature transients have reported that moderate operative temperature changing rate of lower than 0.5 °C/h has no influence on thermal sensation or thermal comfort (acceptability) than in steady states [29,30]; for rate of change greater than 1 °C/h, subjects' thermal sensation generally agrees well with predicted by PMV model (tested up to ±5.0 °C/h) [31–35], but thermal acceptability tends to shrink in the cooler side [31–33]. However, there is no consistent conclusion on the limit of the temperature changing rate within which PMV/PPD will be valid. Still, the suitability of PMV/PPD model for application to DLC events needs to be tested in laboratory experiments and field studies.

3.3.3. Optimizing DLC algorithms for university lecture theatres

The preceding analysis reveals that the majority of DLC scenarios tested had adverse thermal comfort impacts on the occupants. DLC scenarios with higher off cycle fraction, longer cycling period, higher cooling set-point temperature, poorer building envelope thermal performance and higher ventilation rate will induce more occupant thermal discomfort during DLC events. Although a common practice in previous DLC programs, a standard or universal DLC algorithm for all participating premises will not guarantee universally acceptable thermal environments, and run the risk of increased override rates [2,5]. In order to achieve acceptable thermal comfort outcomes, DLC algorithms must be applied judiciously and customized to the specific building. Selection of DLC algorithms in university lecture theatres or any other classroom buildings should take into account cooling set-point temperatures, building envelope thermal performance as well as ventilation rates. Usually in an existing building, the construction type and ventilation rate are already set. If the buildings have relatively poor envelope thermal performance and high ventilation rates, only conservative DLC algorithms with low off cycle fraction, short cycling period and low cooling set-point temperature should be selected; if the buildings have relatively good envelope thermal performance and moderate ventilation rate, more ambitious algorithms can be considered for higher peak demand reduction. However, cycling schemes combining 67% off cycle fraction with 1 h cycling period are not recommended for lecture theatres at any time.

Comparison of 24 pairs of simulation cases with the same off cycle fraction, set-point temperature, building envelope thermal performance and ventilation rate, but different cycling periods (0.5 h vs.1 h) using the independent t-test revealed that the difference in maximum PPD during DLC events, −11.6%, was significant at $p < 0.001$, representing a large-sized effect (Cohen's $d = 1.22$). It suggested that, all else being equal, especially the off cycle fraction which determines the amount of load shedding, shorter cycling period DLC scenarios have less adverse thermal comfort impacts than longer ones. This could be another way of optimizing DLC algorithms. However in practice, cycling periods must not be so short as to cause compressor failures and inefficiencies [14]. The prevailing 0.5 h cycling period in previous DLC programs can serve as an ideal value.

4. Conclusions and suggestions

By simulating a typical university lecture theatre in DesignBuilder and EnergyPlus, this study has explored thermal environments and thermal comfort impacts of DLC events induced by various off cycle fractions, cycling periods, cooling set-point temperatures, building envelope thermal performance and ventilation rates. The following conclusions can be drawn from the present study:

- During DLC events, the air temperature, mean radiant temperature and relative humidity all fluctuate with the AC on and off, forming saw-tooth profiles. Though simulation results suggest high relative humidity, according to other studies, high humidity problems are very common in school buildings with poor dehumidification capability but located in hot and humid climate zones. Use of variable speed fans or Dedicated Outdoor Air Systems can enhance the dehumidification capability of the HVAC system and maintain lower indoor RH during DLC events, which will offset the adverse thermal comfort impacts of DLC due to high RH.

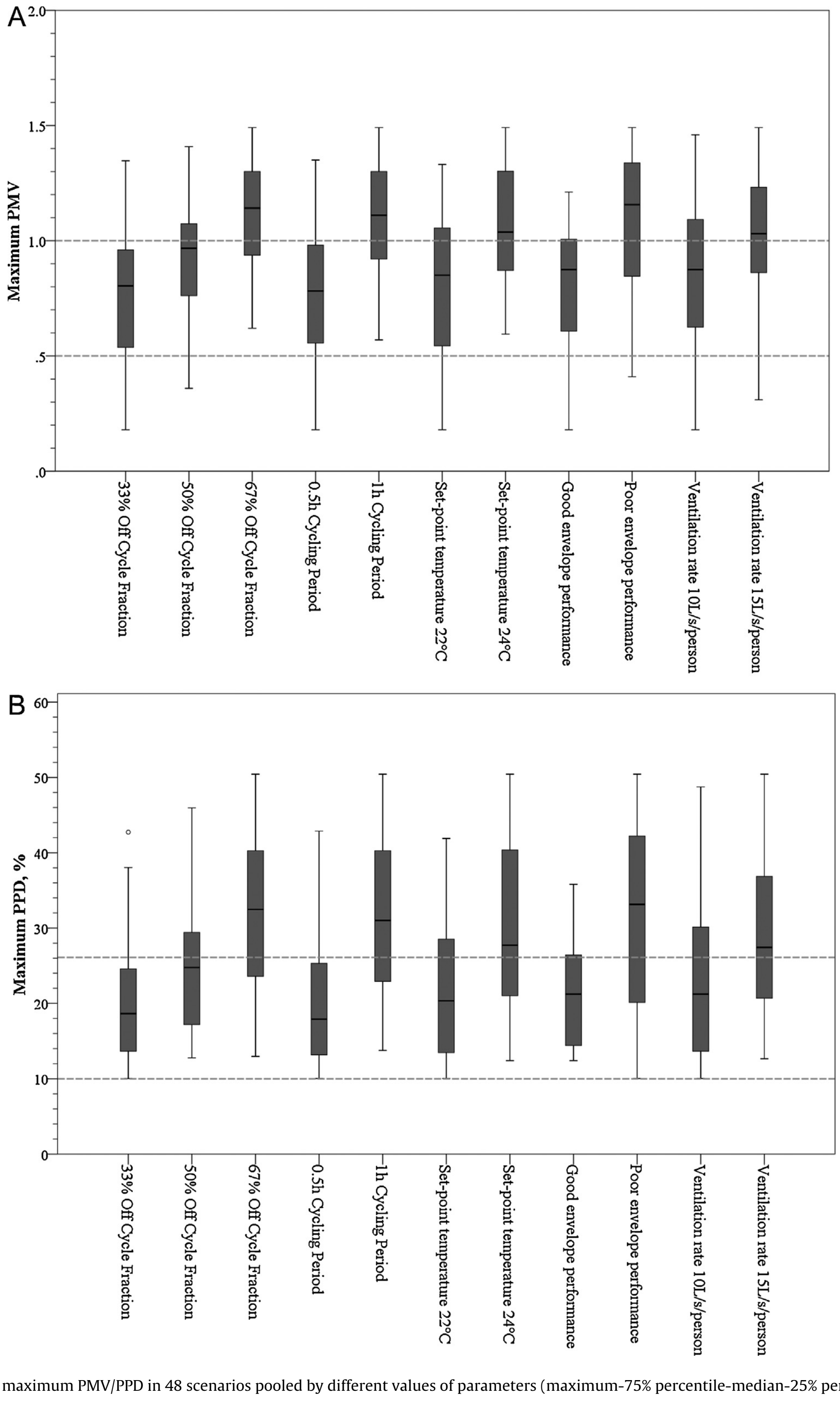

Fig. 10. Boxplot of maximum PMV/PPD in 48 scenarios pooled by different values of parameters (maximum-75% percentile-median-25% percentile-minimum).

- All 5 parameters tested in this study have impacts on thermal environments during DLC events. Under tested conditions which represent typical Australian university lecture theatre settings, off cycle fractions, cycling periods and cooling set-point temperatures have relatively larger influences compared to building envelope thermal performance and ventilation rates.
- Simulation results show that DLC scenarios do not comply with the limits on temperature ramps and drifts specified in ASHRAE 55-2013. Most DLC scenarios have exceeded the permissible thermal comfort range by PMV/PPD method indicated in ASHRAE 55-2013. However, the PMV/PPD index is an indicative-only thermal comfort index. Subjects' actual thermal comfort impacts of

DLC events can only be obtained from laboratory experiments or field studies, which are the focus of future research by the authors.

- In order to maintain acceptable thermal comfort for occupants, DLC algorithms must be applied judiciously and customized to the specific building. Selection of DLC algorithms should take all influencing parameters into account and avoid disadvantageous parameter-combinations. University buildings with poor envelope thermal performance and high ventilation rate should adopt conservative DLC scenarios, while buildings with good envelope thermal performance and moderate ventilation rate can implement more radical DLC algorithms to achieve higher peak demand reduction. All else being equal, DLC algorithms with shorter cycling periods have less adverse thermal comfort impacts than the longer ones, and are therefore recommended for university lecture theatre applications.

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Appendix B: Paper 2

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Statement of Co-Author Contribution

Fan Zhang: As a lead author, Fan Zhang was responsible for the entire process of drafting the manuscript, including literature review, conduct of human subject experiments and data analysis, as well as development of discussions and conclusions.

Richard de Dear: Discussed the experimental design. He assisted Fan Zhang with the results and discussions. The manuscript was reviewed and edited by Richard de Dear.

Christhina Candido: Assisted Fan Zhang with the discussions. Reviewed and edited the manuscript.

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Thermal comfort during temperature cycles induced by direct load control strategies of peak electricity demand management

Fan Zhang*, Richard de Dear, Christhina Candido

Indoor Environmental Quality Laboratory, Faculty of Architecture, Design and Planning, The University of Sydney, Australia

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Direct load control (DLC) is a utility-sponsored demand response program which allows a utility to cycle specific appliances on and off during peak demand periods. Direct load control of air conditioners induces temperature cycles that might potentially compromise occupants' thermal comfort. In two separate experiments, 56 subjects' thermal comfort was closely examined during 6 DLC conditions and 2 control conditions simulated in a climate chamber, representing typical DLC-induced thermal environments in university lecture theatres. Results show that half of the DLC conditions were clearly accepted by subjects. Multilevel linear modelling of thermal sensation demonstrates that operative temperature, vapour pressure and the rate of temperature change are the three most important predictors during DLC events. Multilevel logistic regression indicates that in DLC conditions with lower adapting temperatures, thermal acceptability is significantly predicted by air speed and its interaction with operative temperature whereas in DLC conditions with higher adapting temperatures, by air speed, operative temperature and the rate of temperature change. Subjects' thermal comfort zone during DLC events is wider than predicted by Fanger's PMV/PPD model in that the former is more tolerant of cooler temperatures. Results from this study suggest that ASHRAE 55-2013 is overly conservative in defining the limits for temperature cycles, ramps and drifts.

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1. Introduction

1.1. Direct load control strategy and its impact on indoor thermal environment

Demand response provides an opportunity for consumers to play a significant role in the operation of the electric grid by reducing or shifting their electricity demand during peak periods in response to time-based tariffs or other financial incentives [1]. *Direct load control (DLC)* is a utility-sponsored demand response program which allows a utility to cycle specific appliances on and off during peak demand periods. In exchange, participating customers are entitled to financial incentives or discounted electricity bills. The most commonly targeted appliances in DLC programs are air conditioners, electric water heaters and pool pumps. Air conditioners are the focus of the present study. Direct load control of air conditioners typically consists of duty cycle restriction and temperature setback [2]; the former is the research interest of this paper. Under duty cycle restriction program, the air conditioner compressor is switched on and off at predetermined intervals with the fan on even if the set-point temperature is not met.

For the duty cycle restriction DLC approach, cycling the air conditioner compressors on and off for a given proportion of time will generate repeated rises and falls in air (operative) temperature. Depending on the DLC algorithms and building-specific characteristics, it is possible that indoor temperature fluctuation amplitude exceeds the range of thermal comfort zones in steady states and potentially causes thermal discomfort for building occupants. The previous work of the authors [3] have simulated thermal comfort impacts of 48 DLC algorithms in university lecture theatres where there are much higher occupant density and ventilation rate than the residence and small business buildings, representing a "worst case" scenario for DLC-induced thermal environments. Although most of the simulation cases exceeded the permissible thermal comfort range defined by Fanger's predicted mean vote (PMV)/predicted percentage dissatisfied (PPD) method [4], since the applicability of the PMV/PPD method in transient thermal environments is questionable (refer to the discussion in 1.2), the *actual*

* Corresponding author. Wilkinson Building (G04), The University of Sydney, NSW 2008, Australia.
E-mail address: fan.zhang1@sydney.edu.au (F. Zhang).

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comfort impacts of DLC events must be examined in either laboratory experiments or field studies with human subjects.

1.2. Thermal comfort during temperature cycles, ramps and drifts

ISO 7730-2005 [5] defines temperature cycle as “variable temperature with a given amplitude and frequency”. In ASHRAE 55-2013 [6], cyclic variations refer to “those situations where the operative temperature repeatedly rises and falls, and the period of these variations is not greater than 15 minutes”. The maximum allowable peak-to-peak cyclic variation in operative temperature is 1.1 °C. Temperature ramps and drifts are defined as “monotonic, non-cyclic changes in operative temperature” [5,6]. Cyclic variations with a period greater than 15 min are also treated as ramps or drifts. The maximum change allowed for ramps and drifts in operative temperature during a period of time is shown in Table 1.

Hensen [7] reviews 5 climate chamber experiments on cyclical temperature variations [8–12]. After this review, there has been no recent study on temperature cycles. Table 2 summarises their key experiment design parameters and main results. Regarding the range of comfort zone due to temperature variations, Table 2 reports inconsistent results from the experiments: Sprague and McNall [8] reported narrowed comfort zones with increased rates of temperature change; Wyon and his colleagues [9,10], nonetheless, found the opposite to be true—subjects tolerating greater amplitudes when the temperature changes more quickly; Nevins et al. [11] and Rohles et al. [12], however, concluded that fluctuation-induced comfort zones would not differ much from those obtained in steady state conditions. Possible explanations for these contradictions pointed out by Hensen [7] related to distinct experimental designs, different voting scales, acceptability criteria adopted, test conditions and so on. Despite the confusion he concluded that, with cyclical fluctuating ambient temperatures, the bandwidth of acceptable temperatures decreases with increasing fluctuation frequency, and achieves its maximum under steady-state conditions.

Table 2 also summarises 6 climate chamber experiments on temperature ramps and one experiment on temperature drifts. Berglund and Gonzalez [14] define thermal sensitivity as $\Delta TSV/\Delta T$ where ΔTSV means change of thermal sensation vote (TSV) on the ASHRAE 7-point scale and ΔT means change of operative temperature. In respect to subjects' thermal sensitivity, the experiments consistently show it to be neither affected by clothing [14] nor age [19]. Regarding thermal sensitivity vs. rate of temperature change, no consistent relationship can be observed in these studies. Comparison between TSV and PMV reveals that generally these two parameters are in reasonably good agreement for young subjects [13,17–19]. Knudsen et al. [17] concluded that the PMV model might be possible to predict thermal sensation for a rate of temperature change up to ± 5.0 °C/h. As for thermal comfort zone width compared with steady states, contradictory results have also been reported: Berglund and Gonzalez [14,15] and Schellen et al. [19] reported increased comfort zone width (thermal acceptability) than in steady states; Griffith and McIntyre [13] reported the same comfort zone width; Rohles et al. [16] and Knudsen et al. [17] reported decreased comfort zone while Kolarik et al. [18] reported inconsistent results for different ramps. As mentioned before, discrepant thermal acceptability criteria are likely an important cause of the inconsistent findings; another factor might include human thermoregulation control mechanisms that will be discussed in the following.

1.3. Dynamic thermal comfort and alliesthesia

The most common thermal sensation models are Fanger's PMV model [4] and Gagge's 2-Node model [20], both catering for uniform and steady state conditions. Dynamic thermal sensation models include a derivative that corresponds to sensations induced by changing (transient) conditions, which are correlated with the responses of the body's thermal receptors.

Ring and de Dear [21] and de Dear et al. [22] developed a skin receptor impulse frequency model based on humans' ability to instantaneously detect changes in the thermal environment from the cutaneous thermoreceptors. The cutaneous thermoreceptor response includes both static and dynamic components: the static component being proportional to the *temperature* at the receptor site, and the dynamic component being proportional to *rate of change* with respect to time in local skin temperature. When exposed to a temperature up-step, warm receptors respond with a sudden spike in impulse frequencies, and then decay back to its static response. The cold receptor follows the similar pattern during a temperature down-step, except that the intensity of cold overshoot could be about twice the size of the corresponding warm overshoot derived from the same but opposite direction temperature transient, as have been observed by de Dear et al. [22]. This appears to result primarily from cold receptors being closer to the skin surface than warm receptors, and also from the higher sensitivity of cold receptors to skin temperature change. Fiala et al. [23] proposed a dynamic thermal sensation model from physiological states using a multi-node, dynamic model of human thermoregulation for spatially uniform transient conditions. Zhang et al. [24–26] proposed a model that predicts both sensation and comfort at the local body parts level as well as the whole-body level to evaluate comfort in nonuniform and transient environments; this model cannot predict participants' subjective states (thermal responses) from objective environmental measurements.

Hensel [27] concluded that faster thermal transients required smaller deviations of skin temperature from neutral to produce a just noticeable sensation than was the case for slower temperature transients, meaning that there is a threshold for thermal sensation and it is affected by the rate of temperature change. The threshold of thermal sensation is also determined by the *adapting temperature* (the temperature to which the skin is adapted when the change starts), the direction of temperature change, the exposed part of the body and the area being exposed. Hensen [7] inferred that the latter two factors have partly contributed to the contradictory results in Table 2.

The term *alliesthesia* was coined by Cabanac [28] for homeostatic systems in which a given stimulus can induce either a pleasant or an unpleasant experience, depending on the subject's internal state. De Dear [29] has summarized the concept of alliesthesia as “any external or environmental stimulus that has the prospect of restoring the regulated variable within the *milieu interieur* to its set-point will be perceived as pleasant (positive alliesthesia), while any environmental stimulus that will enlarge the error between the regulated variable and its set-point will be perceived as distinctly unpleasant, or even noxious in more extreme cases (negative alliesthesia)”. Parkinson and de Dear [30] further developed the concept of *spatial alliesthesia*, referring to

Table 1
Limit on temperature ramps and drifts by ASHRAE 55-2013 [6].

Time period, h	0.25	0.5	1	2	4
Maximum operative temperature change allowed, °C	1.1	1.7	2.2	2.8	3.3

Table 2
Summary of thermal comfort studies on temperature cycles, ramps and drifts.

Temperature cycles

References	Sample size	Age group	Thermal conditions	Amplitude/frequency/rate of temperature change	Duration	Voting scales	Implications on the range of comfort zone due to temperature variations
Sprague and McNall [8]	192	College age	M = 1.2 met; I_{cl} = 0.6 clo; T_r = 25.6 °C; RH = 45%; v < 0.15 m/s. ~	Peak-to-peak amplitudes 0.6 °C–3.3°C; 1.7 °C/h–10.9 °C/h; 1.0–2.0 cycles/h	3 h	Discrete/continuous 7 category thermal sensation scale	Decreased comfort zones with increased rate of change
Wyon et al. [9]	8	19–25	T_r = 28 °C, I_{cl} = 0, RH = 50%; T_r = 25°C, I_{cl} = 0.6 clo, RH = 50%.	The amplitude is under subjects' control; 9 °C/h, 30 °C/h	2 h mental work followed by 2 h rest	Spontaneous dial voting when the temperature was too hot or too cold	Increased comfort zones with increased rate of change
Wyon et al. [10]	16	21–28	T_r = 24.5 °C, M = 1.2 met; I_{cl} =0.6 clo; v < 0.1 m/s	Peak-to-peak amplitudes 2 °C, 4°C,6° C,8° C; 15 °C/h, 30° C/h, 45° C/h, 60 °C/h; 1.9–7.5 cycles/h	7 h 48 mins on successive days	A different version of dial voting method	The width of comfort vote distribution increases with higher amplitudes, but discomfort votes increase as well
Nevins et al. [11]	18	19–55	T_r=25 °C; M = 1.2 met; I_{cl} = 0.6 clo; RH = 50%; v = 0.25 m/s	Peak-to-peak amplitudes of 10 °C; 18.7 °C/h on average; 0.9 cycles/h	2 h	ASHRAE 7-point thermal sensation scale and 5 category comfort scale	Same comfort zone as in steady state conditions
Rohles et al. [12]	804	18–23	M = 1.2 met; basal temperature 17.8 °C–29.4 °C; I_{cl} = 0.6 clo; RH = 50%;	Amplitudes 1.1 °C–5.6 °C; 1.1–4.4 °C/h; 0.3–1.5 cycles/h	Variant	9 category thermal sensation scale and 7 category semantic differential comfort scale	Same comfort zone as in steady state conditions

Temperature ramps and drifts

References	Sample size	Age group	Thermal conditions	Amplitude/ range/ frequency/ rate of temperature change	Duration	Voting scales	Thermal Sensitivity	Validity of PMV/PPD methods in predicting thermal comfort zone
Griffiths and McIntyre [13]	32	16–19	T_r = 23 °C; I_{cl} = 0.7–0.9 clo; v < 0.1 m/s; vapour pressure within 10 mb ±2·2 mb	±1.5 °C, ±3 °C, and ±4.5 °C from 23 °C;±0.5 °C/h, ±1.0 °C/h, ±1.5 °C/h	6 h	Bedford Warmth Scale and 7 category subjective voting scale	No difference	Thermal comfort zone agrees well with predicted by PMV/PPD
Berglund and Gonzalez [14]	36	18–28	T_r = 25 °C; M = 1.2 met; I_{cl} = 0.5, 0.7, 0.9 clo; v = 0.1 m/s; T_d = 12 °C	±2 °C, ±4 °C, and ±6 °C from 25 °C; ±0.5 °C/h, ±1.0 °C/h, ±1.5 °C/h	4 h	ASHRAE thermal sensation scale and binary acceptability scale	Higher during ±1.0 °C/h ramp than during ±1.5 °C/h ramp, but inconsistent with ±0.5 °C/h ramp	Thermal acceptability is wider than predicted by PMV/PPD for all ramps
Berglund and Gonzalez [15]	24	19–33	T_r = 25 °C; I_{cl} = 0.32–0.72 clo; v = 0.1 m/s; T_d = 10 °C, 20 °C	23 °C–27.8 °C; 0.6 °C/h	8.5 h	ASHRAE thermal sensation scale and binary acceptability scale	—	Thermal acceptability is wider than predicted by PMV/PPD
Rohles et al. [16]	84	18–22	I_{cl} = 0.8 clo	One-hour drift: 22.3 °C–27.8 °C, Half-hour drift: 22.3 °C–26.1 °C; Up to 4.44 °C/h for one-hour drift, 5 °C/h for half-hour drift	0.5–1 h	9 Category thermal sensation scale and 9 category thermal comfort ballot	—	Thermal comfort zone is slightly narrower than predicted by PMV/PPD
Knudsen et al. [17]	40	21–25	T_r = 19.5 °C, 21.5 °C, 23.5 °C; M = 1.2 met; I_c = 0.8 clo; RH = 50%; vapour pressure 1.28 kPa	±3 °C, ±7.5 °C from 21.5 °C; ±1 °C/h, ±5 °C/h	1.5–3 h	ASHRAE thermal sensation scale and 4 category acceptability scale	No difference	Thermal comfort zone is narrower for both ±1 °C/h and ±5 °C/h ramps in the cooler side than predicted by PMV/PPD model

(continued on next page)

Table 2 (*continued*)

Temperature ramps and drifts								
References	Sample size	Age group	Thermal conditions	Amplitude/ range/ frequency/ rate of temperature change	Duration	Voting scales	Thermal Sensitivity	Validity of PMV/PPD methods in predicting thermal comfort zone
Kolarik et al. [18]	52	19–28	T_r = 24.4, 21.4 °C; M = 1.2 met; I_{cl} = 0.5, 0.7 clo; RH = 50%;	Experiment 1: 22 °C −26.8 °C; Experiment 2: 17.8 °C–25 °C; ±0.6 °C/h, ±1.2 °C/h, +2.4 °C/h, +4.8 °C/h	1–8 h	ASHRAE thermal sensation scale, 4 category acceptability scale	No difference for +1.2 °C/h, +2.4 °C/h, and +4.8 °C/h ramps, but sensitivity is significantly higher for +0.6 °C/h in experiment 1	Decreased comfort zone for 4.8 °C/h ramp; increased comfort zone for 0.6 °C/h in the warm side; same (similar) comfort zone for the other ramps
Schellen et al. [19]	16 (all men)	Young: 22–25; Old: 67–73	T_r = 21.5 °C; M = 1.2 met; I_{cl} = 1.0; v = 0.19±0.03 m/s; RH = 40%	17°C–25°C; First 4 h: +2 °C/h; Last 4 h: −2 °C/h	8 h	ASHRAE thermal sensation scale and 4 category comfort scale	Generally the same for young and old subjects	TSV agrees well with PMV for young subjects, but is 0.5 unit lower for old subjects; slightly increased comfort zone

(M—Metabolic rate; I_{cl}—clo value; T_r—reference/control temperature; RH—relative humidity; v—air speed; T_d—dew point temperature).

the perceptual process derived from rapid changes in local skin temperature driven predominantly by cutaneous thermoreceptors instead of the more conventional whole-body model of alliesthesia driven by load errors of central origin [28,29].

1.4. Research aims

In spite of previous studies on temperature cycles, ramps and drifts, there has been no study to date looking directly at the thermal comfort impacts of temperature cycles induced by direct load control strategies of peak electricity demand management. The present study tries to address this issue through laboratory experiments with university student subjects, simulating lecture theatre settings as a worst-case DLC-induced thermal environment; specifically it elaborates on the following research questions:

- What are subjects' thermal comfort responses to various DLC air conditioning events?
- What are the main environmental and demographic factors that affect subjects' thermal comfort? How do these factors interact with each other?
- How does thermal sensitivity vary between DLC air conditioning events of different frequency and amplitude? How do acceptability results from this study compare with the ASHRAE 55-2013 [6] limits on temperature cycles, ramps and drifts?
- Can the steady-state PMV/PPD model [4,5] reasonably predict thermal sensation and thermal acceptability during DLC air conditioning events? How does the thermal comfort zone change compared with steady states?

2. Methods

2.1. Participants

Two separate experiments on simulated DLC air-conditioning events with different adapting temperatures were performed. Participants for the two experiments were recruited from the university students, regardless of age, degree and discipline. Key anthropometric characteristics of the subject were listed in Table 3. All participants wore a standardised clothing ensemble consisting of a short-sleeve T-shirt, athletic shorts, sandals and their own underwear, representing typical clothing ensemble in Australian universities during summer time. T-shirts and shorts were 100% polyester to avoid any transient absorption and desorption heat effects. The uniform's intrinsic clothing insulation was estimated to be 0.5 clo including the insulation of the chairs (0.1 clo) used inside the climate chamber.

2.2. Experiment conditions

The authors' previous simulation study on thermal comfort impacts of DLC air-conditioning strategies in university lecture theatres [3] have identified off cycle fraction, cycling period, cooling set-point temperature before DLC events and building envelope thermal performance as the most influential factors affecting thermal environments during DLC events. As a *fractional factorial design* [31], 8 DLC algorithms were selected from 48 simulation cases conducted in Zhang and de Dear [3] by the *orthogonal array* method [32]. The orthogonal arrays stipulate the way of conducting the minimal number of experiments that could give the full information of all the factors that affect the performance parameter. For each experiment, participants will experience 1 control condition (no DLC event) and 3 experiment conditions (DLC events). All four conditions in Experiment 1 have a cooling set-point temperature (adapting temperature) of 22 °C whereas 24 °C for conditions in Experiment 2. The simulated operative temperature (t_{op}) and relative humidity (RH) for each condition were illustrated in Fig. 1 and Fig. 2.

2.3. Experimental set-up

The experiments were conducted in the summer of 2014 so that subjects were assumed to be naturally heat acclimatized. A climate

Table 3
Anthropometric characteristics of participants (mean ± standard deviation).

Sex	Number	Age (year)	Height (cm)	Weight (kg)	DuBois area (m^2)
Experiment 1					
Male	14	24.4 ± 4.8	178.1 ± 5.9	79.8 ± 18.9	1.97 ± 0.21
Female	14	27.0 ± 8.1	162.8 ± 7.4	53.9 ± 5.3	1.57 ± 0.11
Total	28	25.7 ± 6.7	170.5 ± 10.2	66.8 ± 19.0	1.77 ± 0.26
Experiment 2					
Male	14	24.1 ± 6.4	174.9 ± 4.1	73.4 ± 9.3	1.88 ± 0.12
Female	14	24.6 ± 6.5	162.9 ± 7.1	56.5 ± 7.0	1.60 ± 0.12
Total	28	24.4 ± 6.3	168.9 ± 8.4	65.0 ± 11.8	1.74 ± 0.19

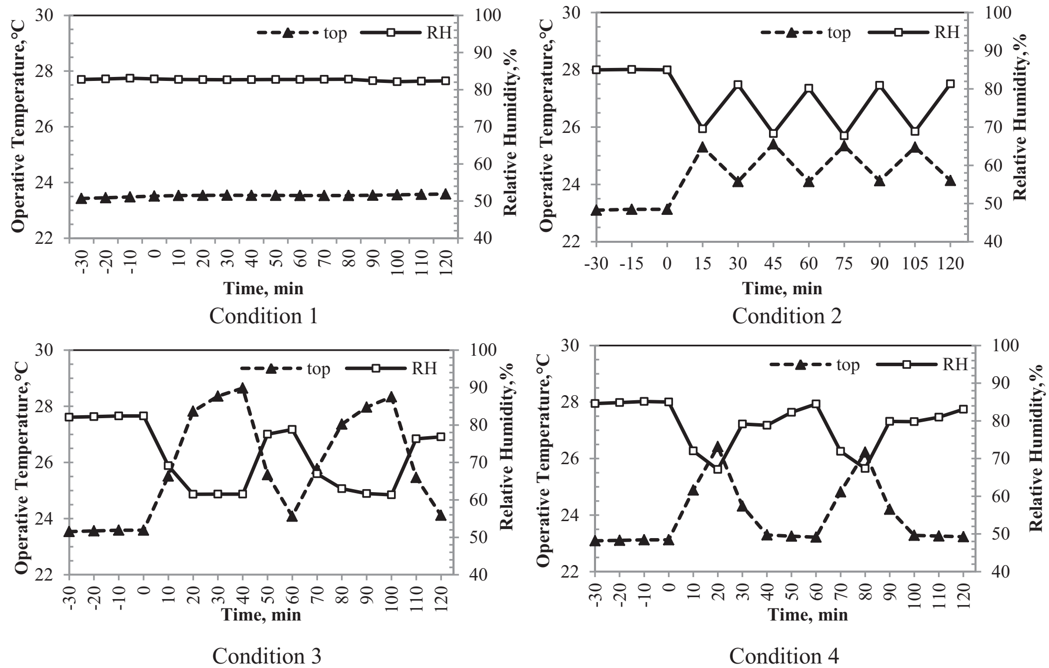


Fig. 1. Simulated operative temperature (t_{op}) and relative humidity (RH) in four conditions of Experiment 1.

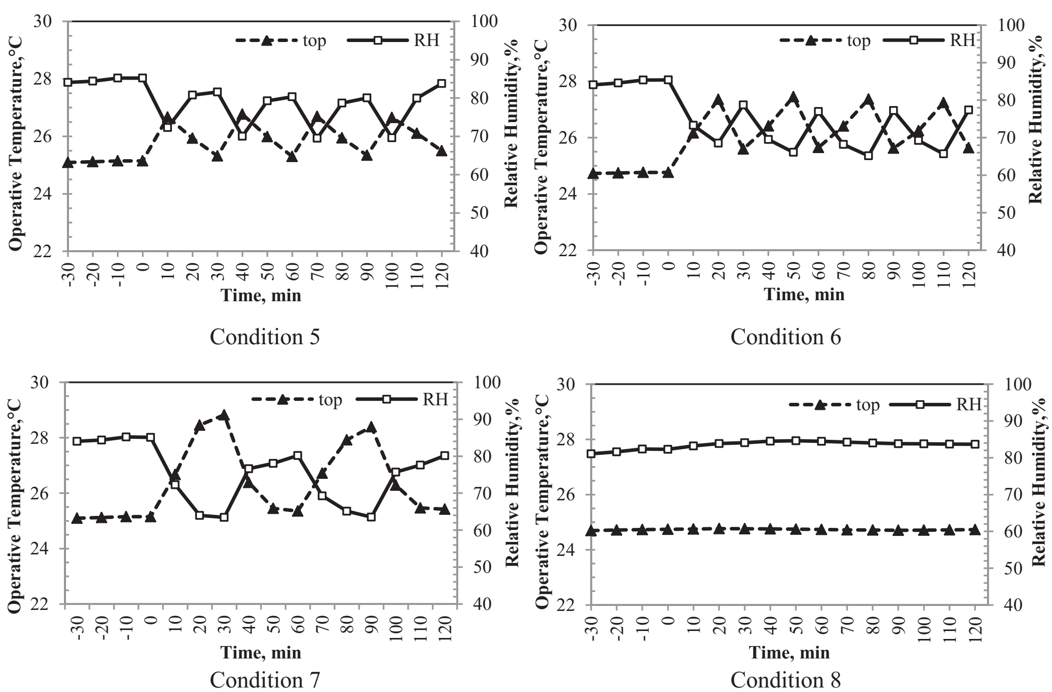


Fig. 2. Simulated operative temperature (t_{op}) and relative humidity (RH) in four conditions of Experiment 2.

chamber (8.85 m × 6.85 m, 2.60 m in height with an accessible raised floor of 250 mm) with temperature and humidity control was used to re-create the various DLC events in the research design and accommodate human subjects. The constant air volume air-conditioning system provided heating and cooling as well as constant fresh air supply at 10 L/s/person during the experiments. The outdoor simulation corridor alongside the climate chamber rendered the typical Sydney DLC event day outdoor condition reported in Zhang and de Dear [3]—30.8 °C. During the experiments, the air temperature, globe temperature, relative humidity and air speed were measured every 5 min throughout every session. The globe temperature was measured at 0.6 m height in the occupied zone using thermistors (±0.2 °C accuracy) inserted in 38 mm Ping-Pong balls painted malt black and served as the control temperature to implement the temperature cycles as depicted in Fig. 1 ad Fig. 2; the air temperature was measured at 1.1 m height in the occupied zone by INNOVA 1221-Thermal Comfort Data Logger; the wall-mounted humidity sensors at 1.7 m height monitored atmospheric moisture in the chamber. Seven fast-response Dantec thermal anemometers (Omnidirectional Transducer 54T21) were mounted at 1.1 m height adjacent to each subject where they measured air speed at a sampling rate of 1 Hz.

2.4. Procedure

In each experiment, 28 subjects were divided into 4 sub-groups. The sequences of experimental conditions to which the four sub-groups were exposed, were balanced in a 4 × 4 *Latin-square design*. All participants were required to attend a 1-h induction session one week before the experiments started. The purposes of the induction were to provide training on the thermal comfort questionnaires and also the cognitive performance tests. Results on cognitive performance tests are not the focus of this paper and will be discussed elsewhere. Participants experienced four conditions throughout four successive weeks. The experimental session lasted for 2.5 h. During the first half hour, participants acclimatized to the cooling set-point temperature (also the adapting temperature, 22 °C for Experiment 1 and 24 °C for Experiment 2). The subsequent 2 h were formal experiment period in which thermal comfort questionnaires were administered to subjects via a bespoke iPad application every 5 min until the session ended. Thermal comfort questionnaires included a 7-point ASHRAE thermal sensation scale (with continuous slider scale to enable real TSV numbers), and a binary thermal acceptability scale. At the end of every session, subjects were presented with a binary overall acceptability question asking about each experimental session's thermal acceptability as a whole.

3. Statistical analysis

Multilevel linear modelling (MLM) is designed to deal with the violation of the assumption of independent errors expected when individuals within groups share experiences that may affect their responses or there are repeated measures for the same individuals. This experimental study is a three-level *repeated cross-sectional* design [33]: thermal environments were clustered within experiment conditions, which are in turn clustered within participants. Each participant attended the same four experiment conditions (including a control condition) in which they were exposed to various thermal environments (determined by the specific DLC event). The Level 1 variables are thermal environmental parameters such as operative temperature, vapour pressure, air speed, rate of temperature change, and time variables such as subjects' length of exposure. The Level 2 variable is the experiment condition. The Level 3 variables are demographic variables, i.e. subjects' age and sex. To manage multicollinearity between predictors and help with interpreting the models, Level 1 variables that do not have a meaningful zero point were centred by their respective grand means [34]. Multilevel linear modelling of participants' thermal sensation was implemented through SPSS Mixed Models, Version 22. Multilevel logistic modelling of participants' thermal acceptability and overall acceptability was implemented by *glmer* function in R, Version 3.2.0.

4. Results

4.1. Thermal perception during DLC events

Fig. S1 depicts the time series data for air temperature and operative temperature monitored in the climate chamber for 6 DLC conditions in two experiments, along with subjects' TSV and thermal acceptability ratings every 5 minutes. For comparison, the calculated PMV results using on-site measured parameters were also plotted on the same graph. The temperature fluctuation amplitudes in Condition 3, 4 and 7 ranged from 5 °C to 7 °C (air temperature) and were higher than those in Condition 2, 5 and 6 which were generally around 3–4 °C. Comparing TSV with the calculated PMV, it is evident that the previously mentioned *overshoot* effect (overestimate of warm and cool sensations) commonly occurred in both sudden warming and sudden cooling stages during all DLC events, with that in large temperature cycles (Condition 3, 4 and 7) being especially pronounced. Also, this overshoot was usually stronger during the first cycle, but was attenuated during subsequent cycles. Thermal acceptability votes in Conditions 2, 4 and 5 were almost above 80% throughout the whole DLC event while in Condition 3, 6 and 7, thermal acceptability strayed from 80% limit for different durations. Detailed experimental effects during DLC events will be discussed in the following sections.

4.2. Predictors of TSV during DLC events

As stated in Section 1.4, this study aims to explore main environmental and demographic factors that affect subjects' thermal sensation and thermal acceptability during DLC events. Steady-state experiments by Rohles [35] and Rohles and Nevins [36] on 1600 college-age students revealed correlations between TSV and temperature, humidity, sex, and length of exposure. Air speed was also a significant predictor for subjects' thermal sensation [4]. However, under transient exposures, the rate of skin temperature change has been clearly demonstrated to be related to thermal sensation in thermal transients [21,37,38]. Schellen et al. [19] reported age difference regarding thermal sensation. The above-mentioned parameters along with experiment condition (Level 2 variable) have been tested in the MLM with possible two-way interactions. The rate of operative temperature change in the ambient environment was adopted instead of the rate of subjects' skin temperature change since the latter was not monitored during the experiments. The rate of temperature change was calculated by the operative temperature change in 5 min, expressed by either a positive or negative value for warm or cold trends in °C/h respectively. Although the air speed was not controlled in the experiment, it was expected to vary from heating to cooling stages in the occupied zone. The monitored values showed a variation between nearly negligible values to 0.18 m/s during heating and cooling stages respectively. Thus, air speed was also tested in the MLM and turned out to be a highly significant predictor.

4.2.1. Level 1 main and within-level interaction effects

There are five main significant predictors that have been detected by both of the experiments—operative temperature, vapour pressure, rate of temperature change, length of exposure and air speed. The operative temperature, vapour pressure and rate of temperature change were significantly positively related to TSV, while occupants' length of exposure in the thermal environment and the air speed were significantly negatively related to TSV. Note that the effect of the rate of temperature change on TSV confirms the previously mentioned *overshoot* effect [21,27]. It is expressed as either a positive/negative value representing a warm/cold overshoot respectively. In the MLM model, the regression coefficients for the rate of temperature change were 0.020 for Experiment 1 and 0.035 for Experiment 2, meaning that if the other predictors remain the same, the rate of temperature change of ±10 °C/h would cause a warm/cold sensation overshoot of 0.20 for Experiment 1 and 0.35 for Experiment 2.

Apart from the main effects, there were significant interaction effects observed between some main predictors, although these effects were not consistent in both experiments. Significant interaction effect means that main predictors not only affect subjects' thermal sensation independently, but also have a joint impact. Specifically, the relationship between TSV and one main predictor would be modified by different levels of values of other main predictors. For Experiment 1, taking Condition 3 as an example, the relationship between TSV and air speed (the regression coefficient) was significantly modified by the value of the operative temperature. If the operative temperature was higher than the mean value in Experiment 1, the air speed had larger negative impacts on TSV than when the operative temperature was lower than the mean value. Similarly, the relationship between TSV and rate of temperature change was also significantly modified by two other parameters—air speed and subjects' length of exposure. The overshoot of subjects' TSV due to a warm temperature change would be ameliorated by a higher air speed that was above the mean value and longer length of exposure in this environment. On the contrary, if the air speed was lower than the mean value and subjects were just exposed to this warm temperature change, the overshoot effect of TSV would be more pronounced.

Experiment 2 produced more interaction effects between the main predictors than Experiment 1. Taking Condition 6 as an example, the relationship between TSV and operative temperature—known as thermal sensitivity—was significantly modified by subjects' length of exposure in this environment. The longer the exposure, the less thermal sensitivity they had. The relationship between TSV and vapour pressure—humidity sensitivity—was also significantly modified by subjects' length of exposure as well as the operative temperature value. However, subjects' length of exposure had a positive impact on subjects' sensitivity to humidity, meaning that the longer they stayed in a humid environment, the larger the impact of humidity on TSV. The operative temperature also had a positive modification on subjects' sensitivity to humidity, which was strengthened at higher operative temperature. There were also two parameters that significantly modified the relationship between TSV and rate of temperature change: the vapour pressure and length of exposure. The overshoot of subjects' TSV due to a warm temperature change was augmented by higher vapour pressure but attenuated by longer length of exposures.

$$Standardized\ coefficent = \frac{unstandardized\ coefficient\ \times\ Standard\ Deviation\ of\ explanatory\ variable}{Standard\ Deviation\ of\ outcome\ variable} \tag{1}$$

4.2.2. Condition effects and cross-level interactions

Experiment condition, the Level 2 variable, was tested by MLM along with interactions with Level 1 main predictors for the two experiments and results are shown in Table 4. It is worth mentioning that the relationship between TSV and centred operative temperature (thermal sensitivity) significantly varied across conditions in both experiments ($p < 0.05$ for Experiment 1 and $p < 0.001$ for Experiment 2). In Experiment 1, Condition 3 had significantly higher thermal sensitivity (0.170 TSV/°C) than that (0.058 TSV/°C) in Condition 1, 2 and 4 ($p < 0.05$). In Experiment 2, the thermal sensitivity in Condition 7 (0.336 TSV/°C) was significantly higher ($p < 0.05$) than that (0.115 TSV/°C) in Condition 5, 6 and 8.

4.2.3. Sex and age effects and cross-level interactions

The effects of subjects' sex and age, as well as their interactions with Level 1 main predictors, were also tested by MLM for two experiments and results are presented in Table 5. Neither sex nor age had a significant effect on thermal sensation during DLC events; nor did these two factors have significant interactions with Level 1 predictors. The only exceptions were an interaction between sex and rate of temperature change in Experiment 2, and an interaction between age and rate of temperature change in Experiment 1.

In order to establish which main predictors or interaction effects (the independent variables) had greater effects on TSV (the dependent variable) in a multilevel multiple regression analysis, standardized regression coefficients which have removed the units of measurement of predictor and outcome variables were calculated for all Level 1 main predictors and interaction effects by applying Equation (1) from Hox [39].

Standardized coefficients reveal that for both experiments, operative temperature, vapour pressure and rate of temperature change were generally the most important predictors for thermal sensation during DLC events. In Hensen's extensive transient thermal comfort literature review [7], he pointed out that four studies on the effect of varying humidity on thermal sensation and thermal comfort [40–43] all indicated that the relative humidity range between 20% and 60% did not have an appreciable effect on the thermal comfort of sedentary or slightly active, normally clothed persons, providing the operative temperature was within or near the comfort zone; relative humidity became more important when conditions were warmer and thermoregulation depended more on evaporative heat loss. Obviously during warm and humid temperature cycles induced by DLC events, relative humidity had a bigger impact on thermal sensation, which could be even more pronounced than the temperature effect.

4.3. Predictors of thermal acceptability during DLC events

Previous literature has not directly looked at how thermal acceptability could be predicted from thermal environmental and demographic parameters. In this study, a multilevel logistic regression has been adopted to identify significant predictors for thermal acceptability during DLC events for both experiments. Table 6 shows predictors for thermal acceptability in both experiments and odds ratios calculated for significant predictors. In Experiment 1, operative temperature was not a significant predictor for subjects' thermal acceptability vote, whereas the air speed and

Table 4
The effect of experiment condition and cross-level interactions on TSV for two experiments.

Level 2 predictors and cross-level interactions	Experiment 1	Experiment 2
Experiment condition	$p < 0.05$	NS
Experiment condition × centred operative temperature	$p < 0.05$	$p < 0.001$
Experiment condition × centred vapour pressure	NS	NS
Experiment condition × centred air speed	NS	$p < 0.05$
Experiment condition × length of exposure	$p < 0.01$	NS
Experiment condition × rate of temperature change	NS	NS

(NS—not significant).

Table 5
The effect of subjects' sex, age and cross-level interactions on TSV for two experiments.

Level 3 predictors and cross-level interactions	Experiment 1	Experiment 2
Sex (Female = 0, Male = 1)	NS	NS
Sex × centred operative temperature	NS	NS
Sex × centred vapour pressure	NS	NS
Sex × centred air speed	NS	NS
Sex × length of exposure	NS	NS
Sex × rate of temperature change	NS	$p < 0.05$
Centred age	NS	NS
Centred age × centred operative temperature	NS	NS
Centred age × centred vapour pressure	NS	NS
Centred age × centred air speed	NS	NS
Centred age × length of exposure	NS	NS
Centred age × rate of temperature change	$p < 0.05$	NS

(NS—not significant).

the interaction between operative temperature and air speed were both highly significant. The odds ratio of air speed implied that holding the operative temperature fixed, thermal acceptability would increase greatly if air speed was higher than the mean value. Similarly, in Experiment 2, there were three significant Level 1 predictors, namely operative temperature, rate of temperature change and air speed. Length of exposure was not significant; however its interaction effect with rate of temperature change was significant. The odds ratio for centred operative temperature indicated that, holding rate of temperature change, centred air speed and length of exposure at fixed values, the odds of voting acceptable would increase if the operative temperature was higher than its mean value 25.9 °C. Similarly, holding the other three parameters fixed, the odds of voting acceptable would go down when the rate of temperature change increases towards the warm direction and go up when the air speed increases from its mean value 0.05 m/s.

4.4. Overall acceptability of tested DLC events and limits on temperature cycles, ramps and drifts

For each subject in each experiment, the proportion of unacceptable votes throughout a DLC event was calculated to represent the proportion of time in a specific condition that this subject felt the thermal environment to be unacceptable (p). This parameter was correlated with subjects' overall acceptability votes in multi-level logistic regression model and was highly significant in predicting overall acceptability in both experiments. Plots of predicted probability of overall acceptability for both experiments were shown in Fig. 3. In order to guarantee a 90% overall acceptability of DLC events, the proportion of time that the thermal environment is deemed unacceptable should not exceed 35%, according to Fig. 3. Applying this criterion to the judgement of overall acceptability for 6 DLC conditions based on the thermal acceptability plots in Fig. S1,

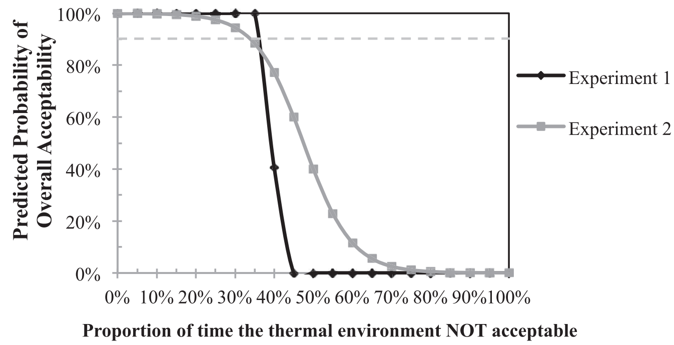


Fig. 3. Predicted probability of subjects' overall acceptability of DLC events against proportion of time the thermal environment is deemed unacceptable.

Condition 2, 4 and 5 were clearly acceptable while Condition 3 was borderline.

Based on the normative 80% thermal acceptability criteria, the permissible maximum operative temperature change from the adapting temperature can be figured out for each DLC condition from Fig. S1. Table 7 shows the maximum operative temperature allowed derived from the two experiments in this study, specifically from Condition 2, 4 and 5. It should be noted that these limits are also dependent on the adapting temperature, its location in the steady-state comfort zone and building occupants' clothing insulation. For example, in Experiment 1, the adapting temperature (operative temperature 23.2 °C) was below the neutral temperature (operative temperature 24.5 °C) whereas in Experiment 2, the adapting temperature (operative temperature 24.9 °C) was around the neutral temperature. Consequently, subjects in Experiment 2 tolerated smaller amplitudes of operative temperature than in Experiment 1 (shown in thermal acceptability plot in Fig. S1). In this study, subjects had light clo values of 0.4, representing typical Australian university lecture theatre settings in summer. However in an office environment, workers tend to have heavier clothes (clo value 0.5–0.6). An increase in clo value is not likely to affect the range of temperatures occupants can tolerate (the deviation from

Table 7
The permissible maximum operative temperature change (°C) based on 80% thermal acceptability criteria derived from the current study compared with ASHRAE 55-2013 [6] (values in the brackets indicate the corresponding limits depicted by ASHRAE 55-2013).

Experiment	Adapting temperature, °C	Time period, h		
		0.2	0.25	0.5
1	23.2	1.8	2.2 (1.1)	3.3 (1.7)
2	24.9	1.7	–	–

Table 6
Estimate of predictors for probability of voting acceptable in both experiments.

Experiment	Fixed effects	Estimate	Std. error	z value	Significance	Odds ratio
Experiment 1	(Intercept)	3.330	0.614	5.425	5.79E-08 ***	27.942
	Centred operative temperature	−0.088	0.191	−0.462	0.644	
	Centred air speed	21.334	8.722	2.446	0.014*	1.84E+09
	Centred operative temperature × Centred air speed	9.955	2.566	3.880	0.0002***	21050.719
Experiment 2	(Intercept)	6.149	0.805	7.636	2.25E-14***	468.151
	Centred operative temperature	−0.847	0.273	−3.100	0.002**	0.429
	Rate of temperature change	−0.128	0.025	−5.022	5.12E-07*	0.880
	Centred air speed	15.786	4.735	3.334	0.001***	7.17E+06
	Length of exposure	−0.303	0.168	−1.804	0.071	
	Rate of temperature change × length of exposure	0.048	0.020	2.397	0.017*	1.049

(***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$).

neutral temperature) if the cooling set-point temperature (adapting temperature) is reduced correspondingly. Comparing with ASHRAE 55-2013 limits [6] for temperature cycles, ramps and drifts (Table 1), the temperature fluctuation amplitudes in all DLC events tested in this study went far beyond (Table 7). On this evidence, it is reasonable to conclude that the ASHRAE limits are overly conservative with temperature fluctuations in that not one of the tested DLC events complied with the ASHRAE standards, yet half of them yielded high thermal acceptability.

5. Discussions

5.1. Thermal sensitivity and numerical model simulations

As mentioned in Table 4, there is a consistent conditional effect (difference) observed in both experiments—subjects' thermal sensitivity in two large temperature cycles (Condition 3 in Experiment 1 and Condition 7 in Experiment 2) was uniformly higher than in smaller temperature cycles or control conditions. Since previous literature implies that thermal sensitivity might be related to rate of temperature change during temperature ramps and drifts (although no consistent result obtained), in this study, the relationship between thermal sensitivity and rate of temperature change was further tested for each experiment condition in both experiments by adding a three-way interaction item in MLM. Results show that in Experiment 1, only Condition 4 detected a significant relationship ($p < 0.01$) between thermal sensitivity and rate of temperature change, while in Experiment 2, both Condition 6 and 7 detected significant relationships ($p < 0.001$ for both conditions). For all three conditions, thermal sensitivity had a positive linear relationship with rate of temperature change, meaning that subjects have higher sensitivity when temperature is changing faster. Taking the range of temperature variations into account for the above conditions, it seems that there is a threshold of temperature amplitudes within which there is no significant difference in subjects' thermal sensitivity. When temperature variation exceeds this threshold, thermal sensitivity increases when temperature changes faster. From the results of this study, the threshold is estimated to be 3–4 °C (air temperature).

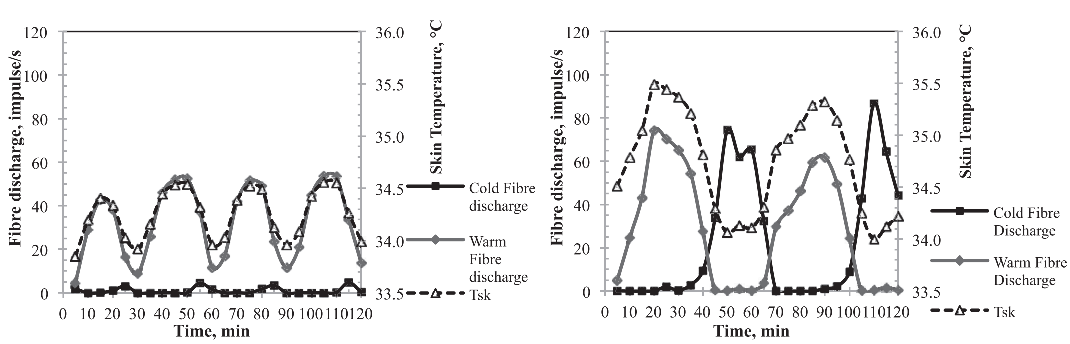
Based on the general properties of cutaneous thermoreceptors, Ring and de Dear [21] and de Dear et al. [22] developed a model based on heat diffusion through the skin for the dynamic response of cutaneous thermoreceptors to temperature stimuli at the skin surface. In this study, the model was used to simulate thermoreceptor impulse frequency during a typical large temperature cycle (Condition 7) and a typical small temperature cycle (Condition 2). Fig. 4 graphs the numerically simulated warm and cold fibre discharge along with the skin temperature for a theoretical subject using measured physical parameters during DLC events. There is larger volume of thermoafferent traffic in the large temperature cycle than in the small one, meaning that in the large temperature cycle the central nervous system receives more neural signals carrying thermal information. Hence, the skin simulation results corroborate with the previous finding that subjects' thermal sensitivity was higher in large temperature cycles than in small ones.

The purpose of ASHRAE limits on temperature cycles, ramps and drifts is to prevent occupants from experiencing discomfort due to fast temperature change, especially to avoid sensation overshoot/shock resulting from the activation of dynamic thermoreceptor response. However, these limits seemed overly conservative when compared with the numerical model simulation results in this study. Although not displayed in Fig. 4, skin simulation results revealed that for even the largest temperature cycles, the warm and cold fibre discharge still predominantly derived from the static (steady-state) response, while the dynamic sensitivity of thermoreceptors remained dormant for most of the time. As Parkinson and de Dear [30] have clearly pointed out, the ASHRAE limits for cycles, ramps and drifts are inconsistent with literature on the role of elevated air movement in extending the upper range of the adaptive thermal comfort zone [e.g. 44–46].

5.2. Validity of the PMV/PPD model and thermal comfort zones during temperature cycles

Previous research literature gives inconsistent conclusions regarding thermal comfort zones during temperature transients. In the current experiments, the percentage dissatisfied calculated from the binary thermal acceptability votes were plotted against TSV using the pooled data from both experiments (Fig. 5). A best-fit 3rd degree polynomial equation derived from the data was also drawn in Fig. 5. In order to compare with previous literature that adopted Fanger's criteria for dissatisfaction (subjects whose TSV is beyond ±1.5 defined as dissatisfied with the environment), a probit analysis was carried out to predict percentage of cold dissatisfied and percentage of warm dissatisfied, and then they were combined into the total percentage dissatisfied (shown in Fig. 5). Fanger's PMV/PPD model is also plotted in Fig. 5 for purposes of comparison.

Fanger's PMV/PPD model failed to predict thermal acceptability in the current experiments since it consistently *underestimated* subjects' acceptability during DLC events. The thermal comfort (80% thermal acceptability) boundaries based on the binary acceptability votes spanned between TSV range of [-1.5, 1.2], which was much wider than the [-0.85, 0.85] range defined by the PMV/PPD model. Also, instead of a symmetric comfort zone around a neutral PMV, the comfort zone developed from binary acceptability votes in the current experiment was displaced to the cooler side



Condition 2 Condition 7

Fig. 4. Simulated warm and cold fibre discharge and the skin temperature for Condition 2 and 7.

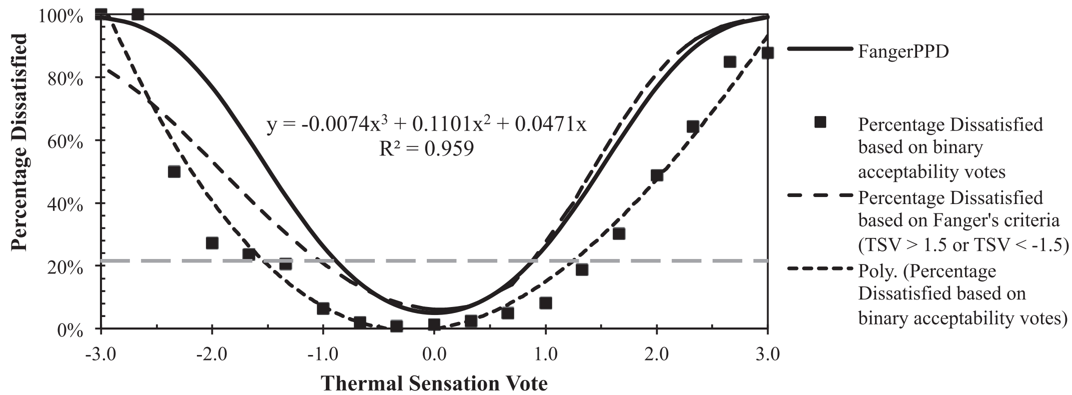


Fig. 5. The relationship between TSV and percentage dissatisfied based on binary thermal acceptability votes, Fanger's criteria (TSV >1.5 or TSV < −1.5) and the PMV/PPD model.

(the magnitude of −1.5 is larger than 1.2), meaning that subjects were more tolerant of cooler temperatures than warmer ones. The percentage dissatisfied based on Fanger's criteria demonstrated close agreement with PPD curve in the warm side (+0.85 for 20% dissatisfaction), however in the cooler side, it defined a wider comfort zone than the PPD curve (−0.97 for 20% dissatisfaction). Comparing two criteria defining the thermal comfort zone, a binary thermal acceptability vote leads to a wider comfort range than the one derived from TSV values. As pointed out by Hensen [7], different acceptability criteria explain the contradictory results in the literature; yet in this study, thermal comfort zone during DLC events was wider than predicted by the PMV/PPD model regardless of the acceptability criteria adopted.

Previous literature has also demonstrated a link between thermal comfort zones during temperature variations and the rate of temperature change, although the exact relationship remains controversial [8–12,18]. In this study, data from two experiments were pooled together and the upper and lower temperature limits of 80% thermal acceptability were determined for various rates of temperature change bins of 5 °C/h interval (Fig. 6). Due to limited range of temperatures tested for each bin, the solid arrow beside the bars indicate that the 80% thermal acceptability limits might go beyond the temperature limits indicated in Fig. 6. There appears to be a bifurcation of thermal comfort zones with the cooling transients being associated with wider comfort zones than their warming counterparts. During the warming temperature transients away from subjects' neutral temperature, the width of comfort zone tends to decrease when the rate of temperature change is higher. This trend can also be observed from Fig. S1 where in two large temperature cycles with relatively higher rate of temperature change (Condition 3 and 7), thermal acceptability drops below 80% at lower temperatures than in smaller cycles with the same adapting temperature. In contrast, during the cooling temperature transients towards the neutral temperature, the comfort zone has been extended towards the warm side. As demonstrated in Fig. S1, there are sudden spikes in thermal acceptability at the initiation of cooling stages in Condition 3, 6 and 7 even if the operative temperature is still 27–28 °C. Relating to the alliesthesia theory, this scenario can be understood as an instance of positive spatial alliesthesia [30]: after being exposed to an upward temperature ramp away from neutral temperature for some time, subjects perceived the sudden convective cooling that was superimposed on warmer-than-neutral temperatures as pleasurable and highly acceptable, because the cooling supply air falling on their heads,

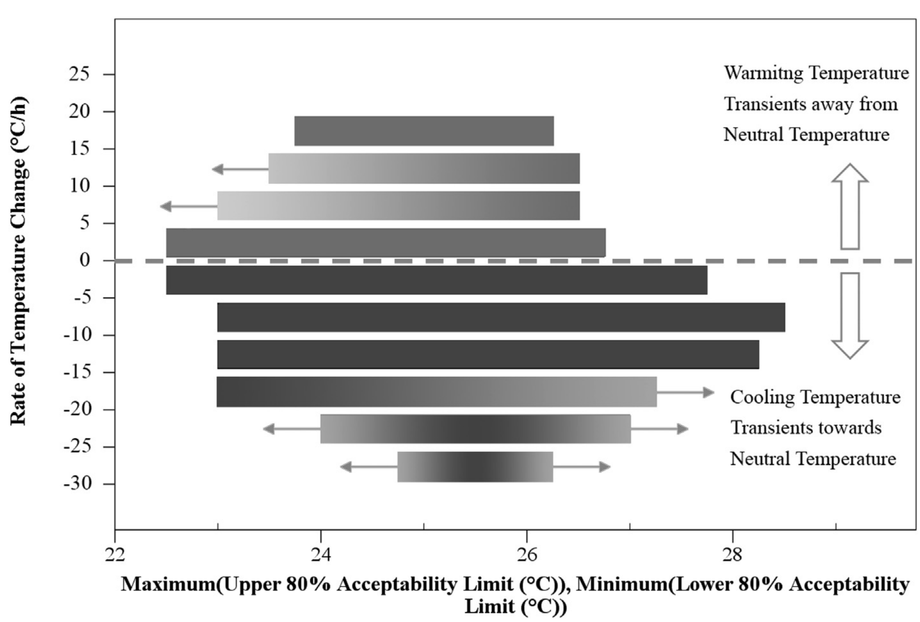


Fig. 6. Breakdown of 80% thermal acceptability temperature limits for various rates of temperature change.

necks effectively offset or countered the thermoregulatory load-error of the warm ambient conditions.

Regarding the impacts of rate of temperature change on the width of comfort zones during cold transients, unfortunately, no strong conclusion could be derived from Fig. 6 due to lack of adequate data for faster cold transients. However, if related to the previous study by de Dear et al. [22], the conclusion could still be drawn that faster cold transients lead to reduced thermal comfort zone. In effect, de Dear et al. [22] has observed conscious thermal sensations approximately twice as sensitive to ambient temperature down-steps as they are to equal magnitude of up-step transients, meaning that subjects have experienced substantial cold sensation overshoot leading to thermal discomfort. However, this higher intensity of cold overshoot is not discernable from Fig. S1 in this study mainly because the rate of temperature change in temperature cycles was much slower than in step-changes. Consequently, it would be reasonable to conclude that thermal comfort zone shrinks during faster thermal transients regardless of the direction of temperature change, which is consistent with Hensel's summary of the transient thermal comfort literature [27].

The extended comfort zone during cooling transients shown in Fig. 6 also reveals an opportunity for non-steady-state indoor thermal environments to achieve the occupant thermal acceptability higher than 80% with adequate local stimulus to offset the load-error—that is, to exploit the phenomenon of alliesthesia. In that case, not only the building energy impacts on the environments could be ameliorated, but also building occupants' sensory function could be activated and energized which overcomes thermal boredom.

6. Conclusions

This experimental study has explored the effects of DLC-induced temperature cycles on university students' thermal sensation and thermal acceptability in lecture theatres (a worst case setting for DLC-induced thermal environments). The following conclusions can be drawn:

- Comparison with TSV and PMV indicates overshoot effects in both sudden warming and sudden cooling stages during DLC events. Out of 6 DLC conditions tested, 3 of them were clearly accepted by subjects.
- During DLC events, operative temperature, vapour pressure, rate of temperature change, length of exposure, air speed, along with several interaction effects significantly predicted subjects' thermal sensation, among which operative temperature, vapour pressure and rate of temperature change were the most important predictors for both experiments. Thermal sensitivity in two large temperature cycles (Condition 3 and 7) was significantly higher than that in small temperature cycles or the control condition. Subjects' sex and age generally did not significantly affect TSV.
- In Experiment 1, air speed and its interaction with operative temperature significantly predicted subjects' thermal acceptability; in Experiment 2, air speed, operative temperature, the rate of temperature change as well as its interaction with subjects' length of exposure all significantly predicted subjects' thermal acceptability.
- Results from current experiments imply that limits on temperature cycles, ramps and drifts defined in ASHRAE 55-2013 [6] are overly conservative since all DLC conditions tested in the experiment went far beyond the standard's limits but still they yielded high levels of thermal acceptability; also, the numerical simulation of thermoreceptors revealed that the dynamic sensitivity of thermoreceptors remained dormant for most of the time during DLC events.
- No matter which acceptability/dissatisfaction criteria were adopted, the thermal comfort zone of our sample during DLC events was wider than predicted by the PMV/PPD model on the cooler side. The thermal comfort zone shrinks when the temperature changes faster regardless of direction of change. Results from this study imply a possibility of achieving 80% thermal acceptability in non-steady-state thermal environment with application of local stimulus—in effect, alliesthesia.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2016.03.020.

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Appendix C: Paper 3

Zhang, F. & de Dear, R. (2016). University students' cognitive performance under temperature cycles induced by direct load control events. *Indoor Air*. Article in press. doi:10.1111/ina.12296.

Statement of Co-Author Contribution

Fan Zhang: As a lead author, Fan Zhang was responsible for the entire process of drafting the manuscript, including literature review, conduct of human subject experiments and data analysis, as well as development of discussions and conclusions.

Richard de Dear: Discussed the experimental design. He assisted Fan Zhang with the results and discussions. The manuscript was reviewed and edited by Richard de Dear.

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University students' cognitive performance under temperature cycles induced by direct load control events

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 theaters, 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°C, 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°C, 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 theaters if DLC algorithms are implemented judiciously.

F. Zhang, R. de Dear

Indoor Environmental Quality Laboratory, Faculty of Architecture, Design and Planning, The University of Sydney, Sydney, NSW, Australia

Key words: Direct load control; Peak demand; Cognitive performance; Temperature cycles; Extended-U relationship; Lecture theaters.

Fan Zhang
Wilkinson Building (G04)
Indoor Environmental Quality Laboratory
Faculty of Architecture, Design and Planning
The University of Sydney
Sydney, NSW 2006
Australia
Tel: + 61 2 8627 4187
Fax: + 61 2 9351 3031
e-mail: fan.zhang1@sydney.edu.au

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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.

Introduction

Direct load control strategy

Due to their size and high occupant densities, university teaching buildings such as lecture theaters 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, and pool pumps. This 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 realize 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 theaters 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 theater during DLC events with variant parameter values and found that the ambient temperatures generally range between 20°C and 32°C during a DLC event. Before any assessment of DLC feasibility in lecture theaters 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?

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 (e.g., Muller et al., 2012; Parsons, 2000; Pilcher et al., 2002; Qian et al., 2015), but there are also studies which reported no effects of heat stress on mental performance (Bell et al., 1964; Colquhoun, 1969; Dean Chiles, 1958; Nunneley et al., 1979), and some even found performance improvement upon initial exposure to heat (Poulton and Kerslake, 1965; Lovingood et al., 1967; Colquhoun and Goldman, 1972). Hancock believed that many factors have contributed to the contradictions, such as task complexity, skill levels of subjects, and duration of exposure. 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) reported that peak performance occurs when the predicted mean vote (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 thermal sensation vote (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 and Fisk (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 and Fisk (2006) clearly presented an inverted-U relationship with performance peaking at 21.6°C (Figure 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 Figure 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.

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 the previous laboratory studies (Kolarik et al., 2009; Newsham et al., 2006; Schellen et al., 2010). Newsham et al.

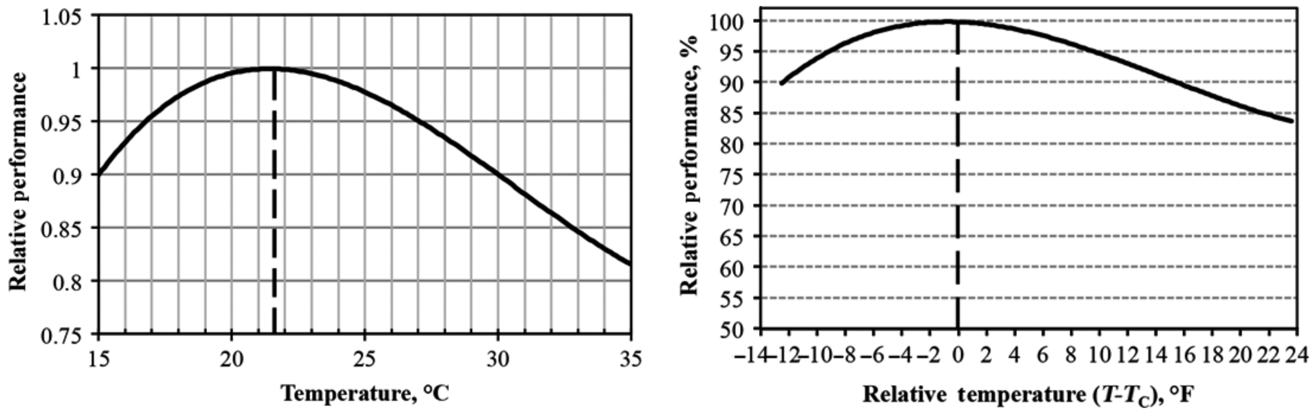

Fig. 1 Relative performance vs. temperature derived from Seppänen and Fisk (2006) (left) and ASHRAE (2013) (right)

(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.

University students' learning performance in lecture theaters

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; Kuncel et al., 2004; Lubinski, 2000). In this study, the generic cognitive skills underlying all learning are measured and served as 'predictors' of university students' academic learning performances in lecture theaters. Specifically, four main cognitive skills are tested—memory, attention, reasoning, and planning.

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. This study is an experimental investigation into how DLC-induced temperature fluctuations affect university students' cognitive performance in lecture theaters 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 the previous research findings, and comments on the controversy surrounding thermal environmental effects on productivity.

Methods

Climate chamber

The experiment was carried out in a climate chamber (8.85 × 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°C to 38°C. 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).

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.

Conditions tested

There were eight environmental exposures in two experiments. Participants experienced one control condition (no DLC event) and three different experimental conditions (DLC temperature cycling conditions) in each experiment. All the six DLC (cycling) conditions were designed on the basis of Zhang and de Dear' (2015) simulated indoor thermal environments of a typical university lecture theater during DLC events with three off-cycle fractions (33%, 50% and 67%), two cycling periods (0.5 and 1 h), two cooling set point temperatures (22°C and 24°C), two building envelope thermal performance levels (good and poor), and two ventilation rates (10 l/s/person and 15 l/s/person). As ventilation rate was found to have the smallest impact on thermal environments during DLC events compared with four 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 theaters).

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 this study, a mixed level orthogonal array of $L_8\ (2^4, 4^1)$ was adopted to test a single factor (off-cycle fraction) with four levels and four other factors (cycling period, cooling set point temperature, building envelope thermal performance, and a blank factor with two 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 two-level factor deliberately left blank to account for experimental 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 and relative humidity (RH) for each condition were illustrated in Figures 2 and 3.

Measurements

Physical and comfort measurements. During the experiments, the air temperature (measured at 1.1 m height above floor in the occupied zone), globe temperature, RH, 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.

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 (Figure 4) came from the public website of Cambridge Brain Sciences (CBS) Inc.[1] and were based on classical paradigms from the cognitive psychology literature.

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 et al., 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

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

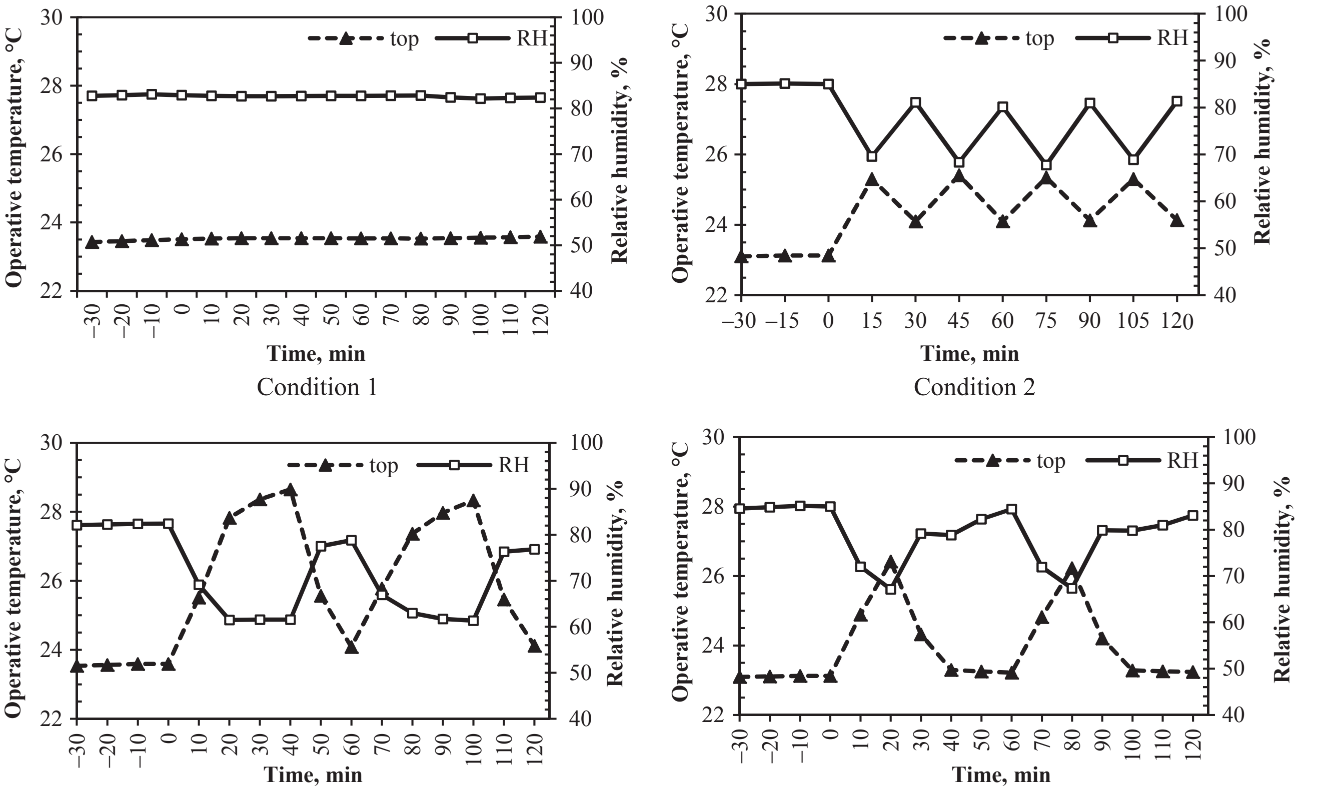

Fig. 2 Simulated operative temperature (OT) and relative humidity (RH) in four conditions of Experiment 1

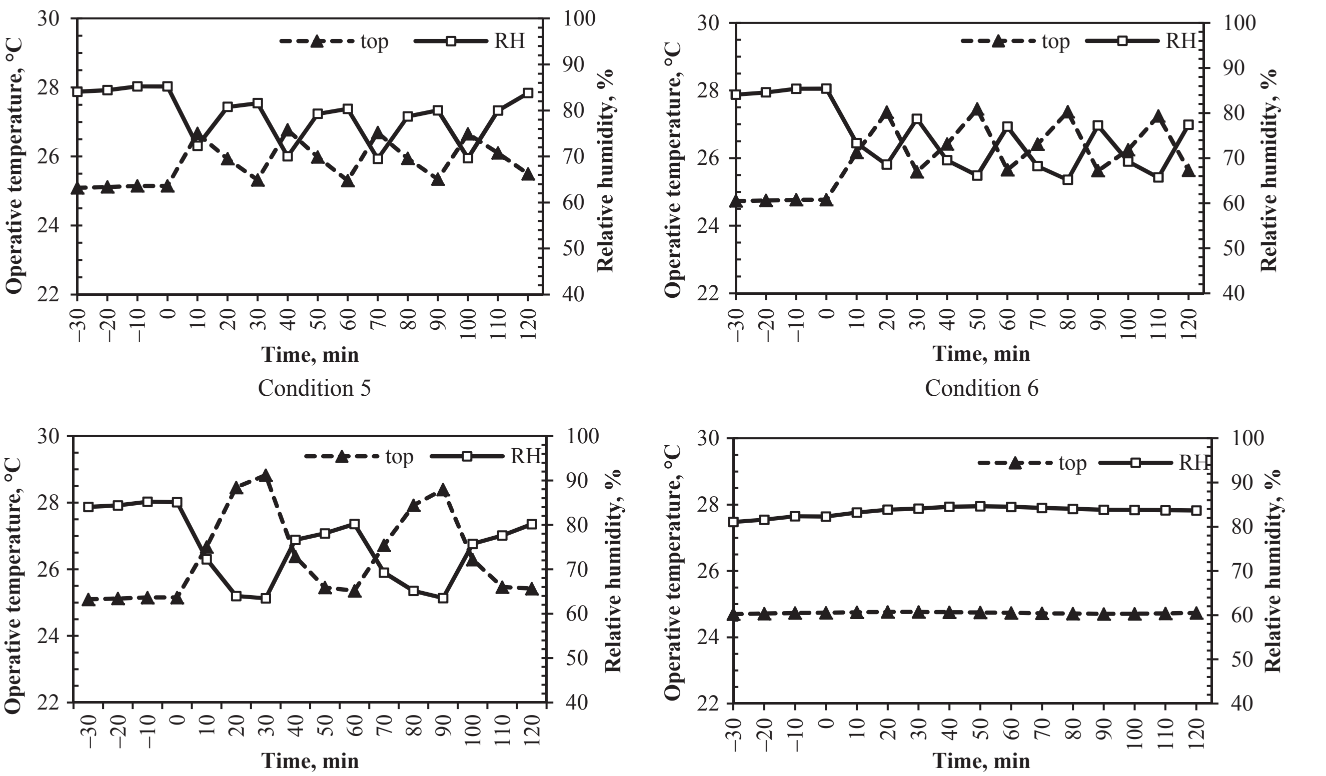

Fig. 3 Simulated operative temperature (OT) and relative humidity (RH) in four conditions of Experiment 2

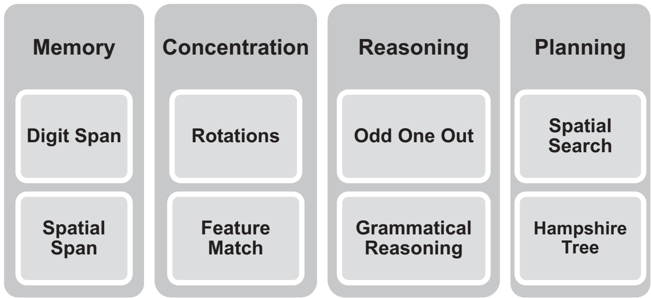

Fig. 4 Cognitive performance tests adopted in each cognitive skill in current experiments

the centre of the screen. In planning skill, the *Spatial Search* is based on a test that is widely used to measure strategy during search behavior (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 eight cognitive performance tests can be found in the Supplemental Information from Hampshire et al. (2012).

Experimental procedure

In each experiment, 28 subjects were divided into four subgroups. Each subgroup has seven subjects sitting in the climate chamber simultaneously. The sequences at which subgroups were exposed to different experimental conditions were balanced by *4 × 4 Latin-square design*.

One week before the experiments started, all participants attended a 1 h induction session to familiarize them with the experimental procedure, receive training and practice 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 h. 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 practiced on the eight cognitive performance tests. The following 2 h 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.

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 analyzed using multilevel linear models (MLM, also known as hierarchical linear models or mixed linear models) although they can be extended to nonlinear 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 centered by their grand mean in each experiment. MLM was implemented through Mixed Models in SPSS 22 (SPSS Inc., Chicago, USA).

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,b), 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 TSV, mean thermal acceptability vote, and calculated mean 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. As 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.

The mean and standard deviation of eight cognitive performance tests in both experiments were listed in Table S2 and compared with corresponding general benchmark results reported in Hampshire et al. (2012)

Table 1 The recorded range of air temperature and effective temperature (ET), mean relative humidity (RH), thermal sensation vote (TSV), predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) with standard deviation (s.d.), mean thermal acceptability for each condition

Experiment	Conditions	Range of air temperature (°C)	Range of ET (°C)	Mean RH ± s.d. (%)	Mean TSV ± s.d.	Mean PMV ± s.d.	Mean thermal acceptability (%)	Mean PPD ± s.d. (%)
1	Condition 1	21.3–23.7	19.7–22.7	75.1 ± 4.2	−0.40 ± 0.81	−0.26 ± 0.13	91	6.8 ± 1.5
	Condition 2	22.0–26.7	20.8–25.1	74.7 ± 4.5	0.11 ± 0.80	0.19 ± 0.25	95	7.1 ± 2.1
	Condition 3	22.2–31.2	20.5–28.6	68.2 ± 7.0	0.67 ± 1.10	0.76 ± 0.57	84	23.7 ± 17.1
	Condition 4	21.7–29.0	20.0–27.1	72.7 ± 5.0	−0.10 ± 0.94	0.01 ± 0.41	90	8.6 ± 4.1
2	Condition 5	23.6–28.8	21.6–26.6	72.1 ± 4.8	0.36 ± 0.92	0.53 ± 0.25	93	12.2 ± 6.2
	Condition 6	23.1–29.7	21.1–27.4	69.7 ± 5.5	0.57 ± 0.98	0.72 ± 0.29	82	17.6 ± 8.2
	Condition 7	23.2–31.5	21.4–28.9	69.5 ± 5.9	0.58 ± 1.12	0.80 ± 0.48	81	23.0 ± 16.9
	Condition 8	23.0–25.5	21.4–24.1	75.4 ± 4.0	0.15 ± 0.76	0.19 ± 0.14	98	6.2 ± 1.1

based on all users of the CBS Web site. 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, to compare test scores between different participants and cognitive test types, each participant's score was normalized 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.

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, as the learning effect of each subgroup may vary between different experimental conditions, as reported by Cui et al. (2013a,b). Furthermore, there may be fatigue effects superimposed upon learning effects because each participant took two sets of the eight cognitive performance tests within each 2-h 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 eight 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 eight 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, the results need to be adjusted for them before treatment effects can be thoroughly explored.

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

Cognitive performance test	Experiment 1	Experiment 2
1. Digit Span	$P < 0.05$	NS
2. Rotations	$P < 0.05$	NS
3. Odd One Out	NS	NS
4. Spatial Search	NS	NS
5. Spatial Span	NS	NS
6. Feature Match	NS	NS
7. Grammatical Reasoning	NS	NS
8. Hampshire Tree	NS	$P < 0.01$
Overall cognitive performance	$P < 0.05$	NS

NS, not significant.

Effects of experimental conditions on cognitive performance

Within-subject comparisons. After adjustment for significant sequence effects, the effect of experimental conditions on participants' eight 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 were calculated for eight cognitive performance tests in both experiments, after adjustment for significant sequence effects

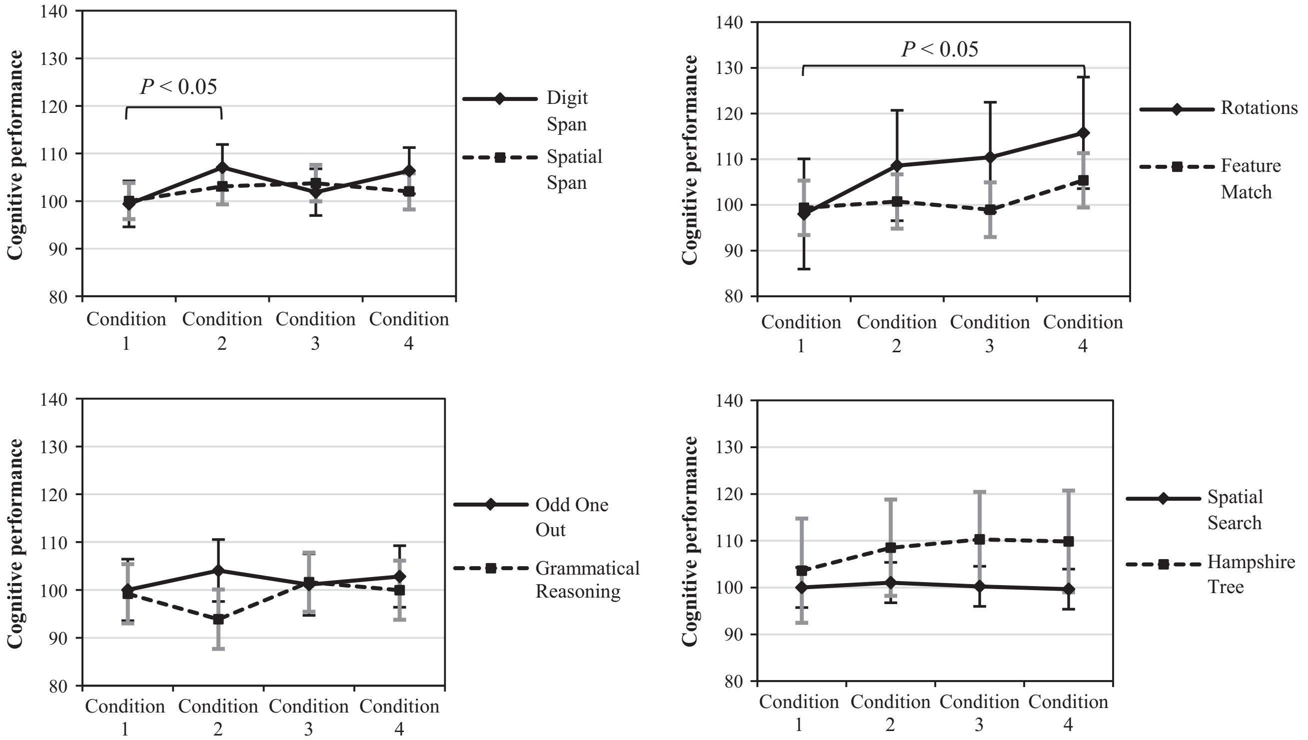

Fig. 5 Estimated marginal means of eight cognitive performance tests with 95% confidence interval (CI) in Experiment 1 after adjustment for significant sequence effects

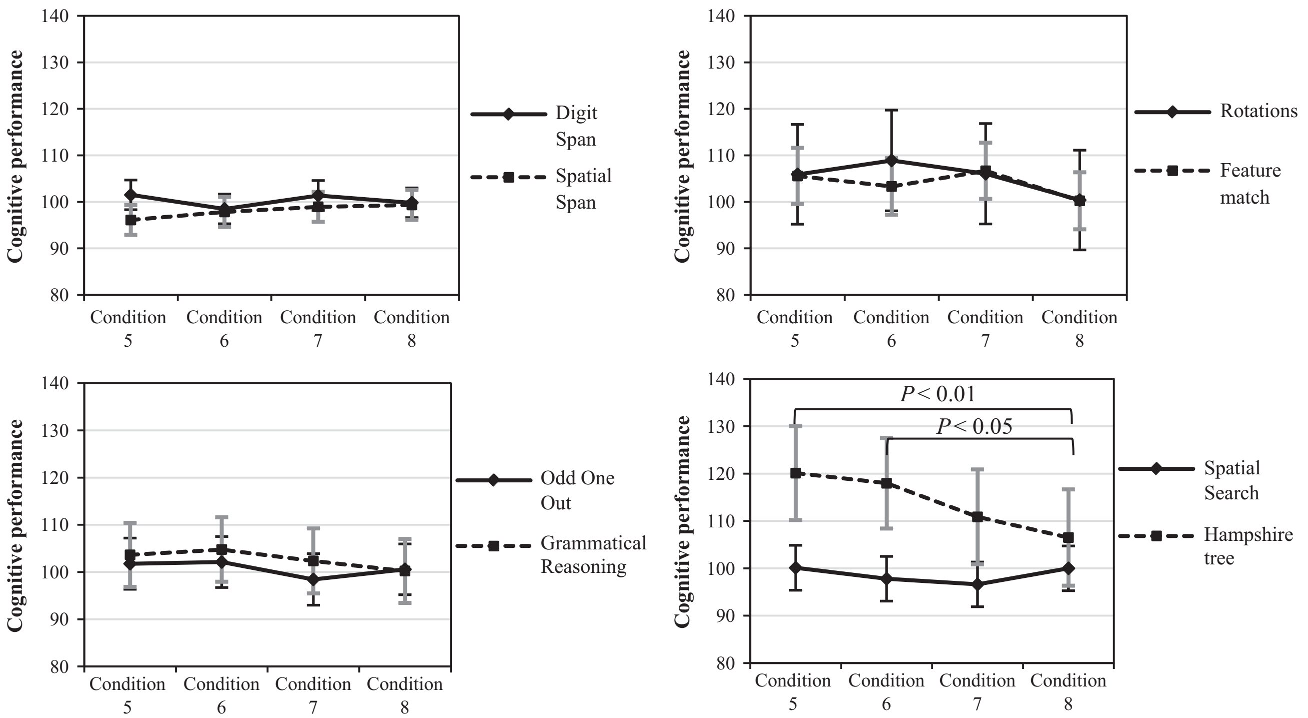

Fig. 6 Estimated marginal means of eight cognitive performance tests with 95% confidence interval (CI) in Experiment 2 after adjustment for significant sequence effects

(illustrated in Figures 5 and 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 generalization: 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. Figure 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).

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 intra-individual differences resulting from the two environmental exposures. However, normalizing 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.

For the majority of cognitive tests, performance scores under the various DLC temperature cycling conditions of Experiment 1 (from cooling set point of 22°C) did not significantly vary from their counterparts in Experiment 2 (cycling from cooling set point 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, Conditions 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 Conditions 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 seven temperature cycles were examined—2 and 4°C/8 min; 2, 6, and 8°C/16 min; and 4 and 8°C/32 min—results from this study do not show any significant difference in cognitive performance between large temperature cycles (Conditions 3, 4, and 7) and small temperature cycles (Conditions 2, 5, and 6).

Effects of different cycling stages on participants' four cognitive skills

As discussed in section *Experimental procedure*, two groups of cognitive performance tests representing four generic cognitive skills were assigned to participants at different points in the DLC-related 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 six 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 set point), 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.

Relationship between cognitive performance and thermal environment

Subjects' cognitive performance was tested against commonly used thermal comfort indexes, including instrumental observations of operative temperature

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

(R) Reference group	(E) Experiment-2 groups	Sequence effects of experimental weeks	Sequence effects within an experimental session	Significant performance tests	Mean difference (E–R)	Significance
Condition 2	Condition 5	NS	NS	Spatial Span	−7.00	$P < 0.05$
	Condition 6	NS	NS	Digit Span	−8.57	$P < 0.01$
Condition 3	Condition 5	$P < 0.05$	NS	Spatial Span	−7.62	$P < 0.01$
	Condition 6	$P < 0.05$	NS	Spatial Span	−5.61	$P < 0.05$
	Condition 7	$P < 0.05$	NS	Spatial Span	−5.64	$P < 0.05$
Condition 4	Condition 5	NS	NS	Spatial Span	−5.93	$P < 0.05$
	Condition 6	$P < 0.05$	NS	Digit Span	−7.24	$P < 0.05$

NS, not significant; DLC, direct load control.

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

Conditions	Sequence effects of experimental sessions	Sequence effects within experimental session	Cognitive skills tested	Mean difference (cycling on–cycling off)	Significance
Condition 2	NS	NS	Reasoning	−10.20	$P < 0.05$
Condition 3	$P < 0.05$	NS	Memory	−5.40	$P < 0.05$
Condition 5	$P < 0.001$	NS	Planning	13.07	$P < 0.05$
Condition 6	1st order $P < 0.01$; 2nd order $P < 0.05$	NS	Planning	13.09	$P < 0.01$
Condition 7	$P < 0.05$	NS	Planning	10.78	$P < 0.05$

NS, not significant; DLC, direct load control.

and subjective TSV, and these relationships were compared with the previously published research findings. The correlation between the cognitive performance and the rate of temperature change as well as cognitive performance and thermal acceptability was also tested. According to the previous literature (Hensel, 1981; Hensen, 1990), the rate of temperature change is related to occupants' thermal sensation during thermal transient conditions; thus, it 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.

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, centered air temperature (c-Ta), rate of temperature change, and thermal acceptability. Based on the previous literature, both TSV and centered 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 Tables 5 and 6 for Experiments 1 and 2, respectively.

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 centered 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 centered 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-Ta^3 (coef-

Table 5 Dependence of test scores in four cognitive skills on thermal sensation vote (TSV), centered air temperature, rate of temperature change, and thermal acceptability—Experiment 1 with cooling set point of 22°C

Cognitive skills tested	Sequence effects of experimental sessions	Sequence effects within experimental session	TSV	TSV^2	TSV^3	c-Ta	$c\text{-}Ta^2$	$c\text{-}Ta^3$	Rate of temperature change	Thermal acceptability
Memory	0.94	0.23	0.64	−1.01	0.13	0.72[a]	−0.16	0.10	−0.004	3.70
Concentration	4.37***	0.60	0.04	−0.03	−0.02	1.13	0.16	0.04	0.26*	4.90
Reasoning	2.68**	0.36	0.89	−0.59	−0.002	0.52	0.06	0.01	0.12	5.15
Planning	1st order 18.68***; 2nd order −2.64**	1st order −10.95*; 2nd order 2.48*	1.85	0.22	0.60*	0.02	−0.07	−0.01	−0.11	−4.16

[a]$0.05 < P < 0.08$.
*$P < 0.05$.
**$P < 0.01$
***$P < 0.001$.

Table 6 Dependence of test scores in four cognitive skills on thermal sensation vote (TSV), centered air temperature, rate of temperature change, and thermal acceptability—Experiment 2 with cooling set point of 24°C

Cognitive skills tested	Sequence effects of experimental sessions	Sequence effects within experimental session	TSV	TSV^2	TSV^3	c-Ta	$c\text{-}Ta^2$	$c\text{-}Ta^3$	Rate of temperature change	Thermal acceptability
Memory	0.89*	−0.16	1.01	0.11	0.15	0.52	0.28	0.05	0.08	−0.39
Concentration	1st order 19.81**; 2nd order −2.95*	0.17	1.34	−0.10	0.10	1.03[a]	0.29	0.06	0.09	3.38
Reasoning	5.93***	1.56*	0.33	−1.05*	0.51	−0.58	−0.31[a]	−0.07*	−0.09	4.67[a]
Planning	1st order 15.77**; 2nd order −2.81**	2.48**	−5.19***	1.54	0.22	−3.15***	0.65*	−0.10	−0.54***	11.52**

[a]$0.05 < P < 0.08$.
*$P < 0.05$.
**$P < 0.01$.
***$P < 0.001$.

ficient −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, the planning performance was significantly related to centered 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.

Relationship between overall cognitive performance and thermal comfort indexes. In the previously published literature on thermal effects on performance (Lan and Lian, 2009; Lan et al., 2011; Seppänen and Fisk, 2006), 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 were also analyzed 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.

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

Table 7 Quantitative relationship of overall cognitive performance index with thermal sensation vote (TSV), centered air temperature, rate of temperature change, and thermal acceptability in two experiments

Experiments	Sequence effects of experimental sessions	Sequence effects within experimental session	Interaction effect	TSV	TSV^2	TSV^3	c-Ta	c-Ta^2	c-Ta^3	Rate of temperature change	Thermal acceptability
Experiment 1	1st order 9.05***, 2nd order −1.13*	0.08	–	0.64	−0.45	0.14	0.32	−0.02	−0.001	0.11*	2.61
Experiment 2	1st order 8.95***, 2nd order −1.34**	−0.32	0.23*	−0.49	−0.73*	0.10	−0.22	0.09	0.003	−0.05	5.03**

*$P < 0.05$.
**$P < 0.01$.
***$P < 0.001$

faster toward 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 the performance scores in an acceptable thermal environment were 5.03% higher than in an unacceptable environment.

Discussion

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 Experiments 1 and 2 helped to understand the joint effects of heat intensity and the duration of exposure.

As 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 (Cui et al., 2013a,b; Lan et al., 2011). 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. The previous studies have shown that high incentives increase subjects' motivation which may override mild deleterious effects of environmental exposure (Cui et al., 2013b; Lan et al., 2010; Pepler, 1958). Cui et al. (2013b) also found that motivation was a better predictor of human performance than environmental temperature. In this study, 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.

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 Tables 5 and 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 Ganey, 2003; Hancock and Warm, 1989)—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 toward the margins beyond the comfort zone (Figure 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 behaviors 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 Tables 5–7. 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).

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, 2014), the weight of evidence does not favor 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 labor in an office building is orders of magnitude higher than the HVAC operational energy costs (e.g., Lan and Lian, 2009; Roelofsen, 2002; Seppänen, 1999; Woods, 1989), 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

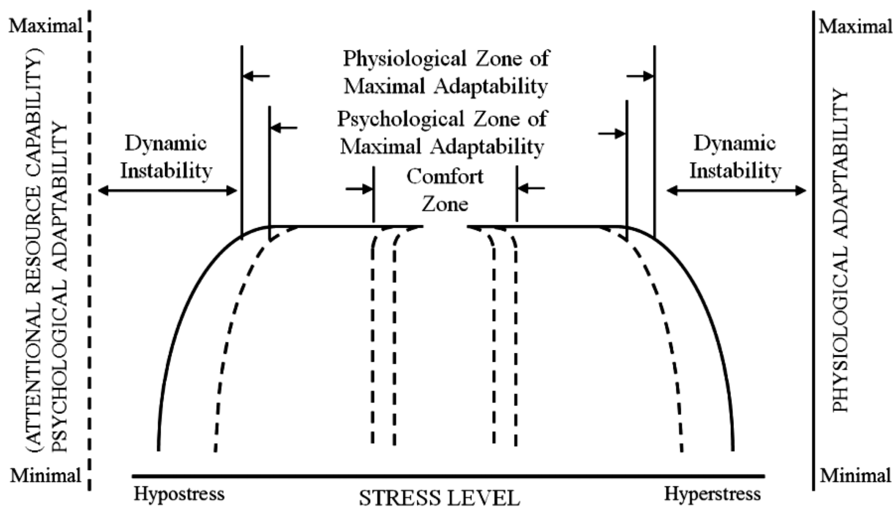

Fig. 7 The extended-U model between stress and performance (Hancock and Ganey, 2003; Hancock and Warm, 1989)

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 thermophysiological responses, and cognitive performance decrements. Several researchers have proposed the effective temperature (Houghton and Yagloglou, 1923a,b) 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 thermophysiological 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.

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 the 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 theaters.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Figure S1. Experimental schedule for two experiments and timing of 8 cognitive performance tests.

Figure S2. Estimated marginal means of overall cognitive performance with 95% CI in two experiments after adjustment for significant sequence effects.

Figure S3. Estimated marginal means with 95% CI of the *Digit Span* and the *Spatial Span* cognitive tests.

Table S1. The environmental conditions tested in experiments.

Table S2. Comparison of mean and standard deviation for 8 cognitive performance tests obtained by the current experiments compared to the broader benchmark scores reported by Hampshire et al. (2012).

Table S3. Tests of sequence effects on cognitive performance in Experiment 1.

Table S4. Tests of sequence effects on cognitive performance in Experiment 2.

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