Optimising thermostat settings in school and office buildings for thermal comfort, cognitive performance and energy efficiency

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Keywords: Energy conservation; HVAC; Schools; Offices; Cognitive performance; Thermal comfort

Abstract

The Jevons Paradox predicts that any increase in energy efficiency will lead to an increase in energy use. This occurred recently in Denmark when the energy efficiency of domestic heating was increased by improving the thermal insulation of dwellings – there was a "Jevons rebound" in the energy used for heating as increased energy efficiency made it affordable to raise indoor temperatures. Raised temperatures and correspondingly lighter clothing mean that activity levels can vary more between occasions without the need to adjust clothing insulation to maintain thermal comfort. This article suggests that a Jevons rebound need not occur when the energy efficiency of heating or cooling in school or office buildings is increased. Research published in recent months has shown that cognitive performance is reduced as the indoor temperature is increased **even if subjective thermal comfort is maintained**. Thermostats should therefore be set at the lower bound of the thermal comfort range: this will save energy when heating and improve performance when either heating or cooling. Additionally, the thicker clothing that will be required means that even the small adaptive variations in activity level that occur while sedentary will be sufficient to maintain thermal comfort. These recommendations apply also to dwellings in which office work is being performed.

Introduction

Energy efficiency in space heating

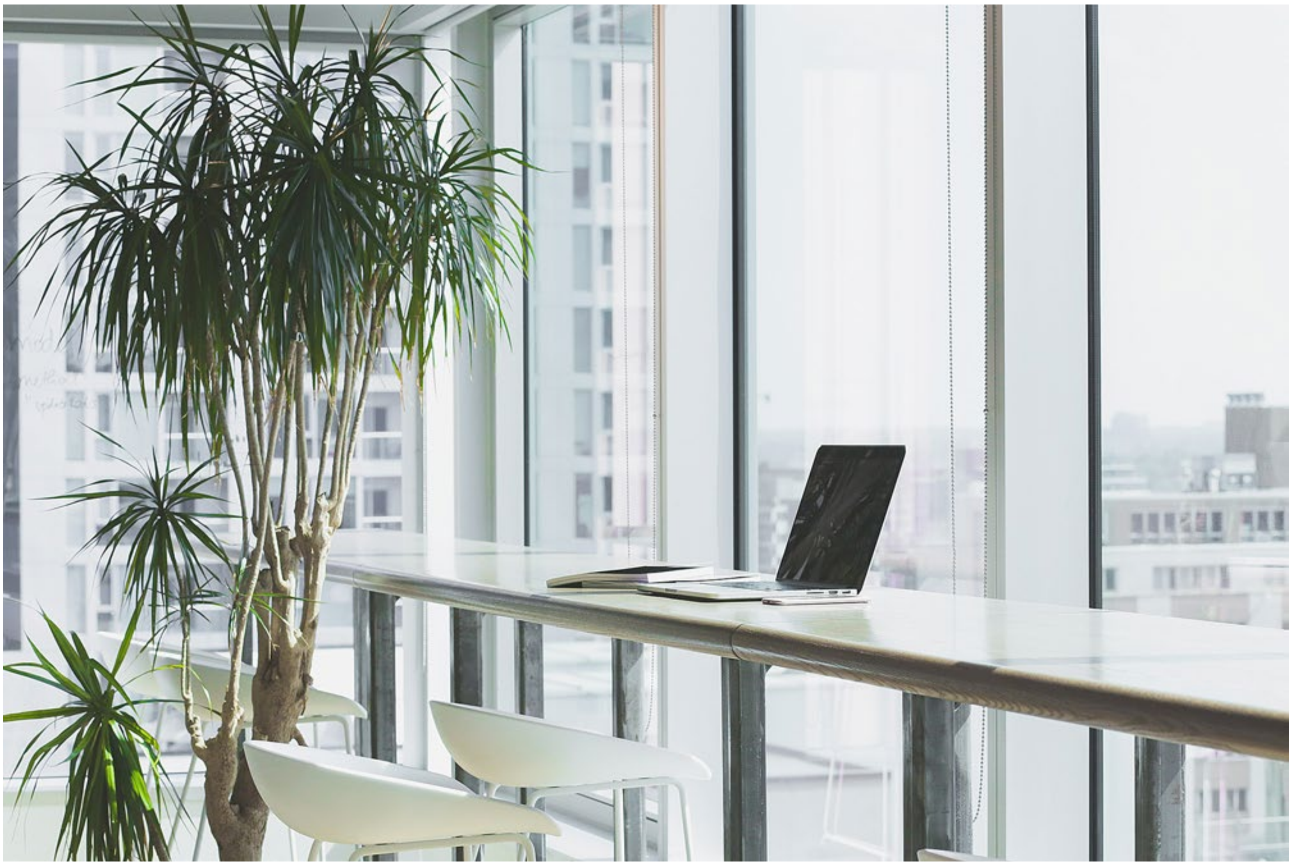
A recent survey examined energy use for heating in 230 000 newly-built Danish dwellings (Gram-Hanssen & Hansen 2016) whose energy-efficiency categories ranged from Category A, the most energy-efficient, to G, the least energy-efficient. In Category A, the actual energy use was 80% **more** than expected, while in Category G, it was 48% **less** than expected. Engineering calculations for both categories had assumed that user behaviour would be the same in all energy-efficiency categories and on this basis had predicted that households living in Category A dwellings would use 84% less energy than households living in Category G. In fact, they used only 45% less – a return on the investment in energy efficiency, certainly, but much less than would be expected if user behaviour had remained the same. As some households were found to use 2 or 3 times as much energy as other households, even in identical buildings, the conclusion was that household behaviour determines energy use and that energy use will increase when the energy and economic cost of space heating is reduced.

The Jevons Paradox may increase indoor temperatures

The authors of the report did not measure indoor temperatures, but they concluded that households living in energy-efficient buildings may have raised indoor temperatures, heated more rooms, or opened windows more often to improve indoor air quality. The result was that as much as half of the expected saving in space heating costs had been used to improve occupant comfort. This is an example of the Jevons Paradox (Freire-Gonzalez & Puig-Ventosa, 2015), which was formulated in 1865 when it was found that increasing the efficiency of steam engines led to more coal being used, not less as engineers had expected. What had happened was that as the cost of whatever benefit was obtained from steam energy decreased, it became economically possible to use more of it. Since that time, this "Jevons rebound" in energy use has been found to hold quite widely in the industrial and transport sectors, e.g., when more efficient airplane engines lead to more air travel, more efficient cars are driven further, and LED lighting is left switched on for longer. In a recent review, Brockway et al. (2021) showed that the economy-wide rebound in energy use following an increase in energy efficiency has been close to the 50% found in Danish dwellings. There is therefore a real risk that energy efficiency improvements in school and office buildings might result in a similar rebound, so if this is to be prevented, it is important to understand the mechanisms involved.

Activity levels and thermal comfort

The authors of the Danish report concluded that the reason thermostat settings had been raised in the more energy-efficient buildings was "so that the occupants could wear summer clothing all year round". It is worth noting that this is not a fashion fad that can be "nudged" (influenced subconsciously), because it provides a real advantage in dwellings: when wearing light clothing, the range of activity levels that is possible without experiencing hot or cold discomfort is much wider than it is for thick, better-insulating clothing. Calculations made with ISO 7730/ASHRAE Standard 55 assumptions indicate that an increase in activity level from 70 to 100 W/m² (1.2 to 1.7 MET)



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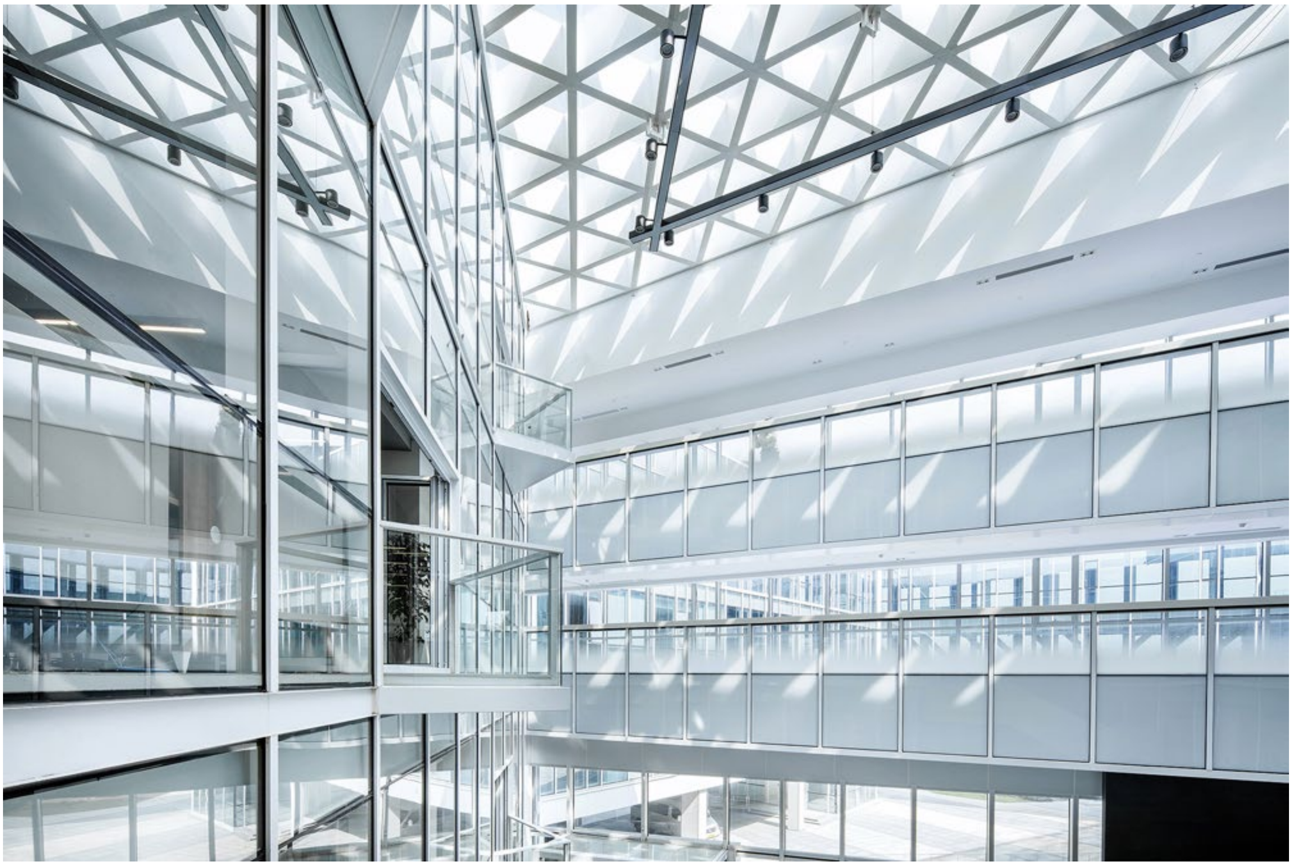
at the operative temperature that is neutral at the lower (sedentary) level of activity would increase the percentage dissatisfied with the thermal environment (i.e., PPD) from 5% to 26% if occupants were wearing thick clothing (1.0 clo), but to only 9% if they were wearing thin clothing (0.5 clo). Additionally, if sweating becomes necessary for heat balance to be maintained at raised activity levels, thin clothing ensembles intended for use in summer weather will usually have a lower vapour diffusion resistance than thick clothing does, allowing sweat to evaporate and provide additional cooling, which would then extend the comfortable range of activity levels still further upwards. The rebound in energy use for space heating is caused by the understandable wish for this additional freedom of action without constantly having to adjust clothing insulation levels to match leisure activity levels, in which the rate of metabolic heat production varies more widely than during the standardized activities that take place in schools and offices. The primary purpose of a dwelling is to provide comfort and convenience for leisure activities, and it appears that householders in Denmark are prepared to re-invest about half of the cost and energy savings provided by energy-efficient buildings to achieve these goals. However, it is worth noting that in an increasing proportion of dwellings, one or more occupants now work from home. This trend was accelerated by the social isolation and lockdowns required to control infection rates during the 2020-2021 Covid-19 pandemic but may continue beyond it. These dwellings must be able to provide an indoor environment that is optimal for office work, which as will be seen below may reduce the above-mentioned Jevons rebound.

Discussion

Offices and schools

If the occupants of offices and schools were as free to adjust their thermostats as householders are at home, the same mechanisms would probably increase indoor temperatures over time, especially as they would not have to pay for the rebound in energy costs in the way that householders do. However, the primary purpose of office and school buildings is not to provide comfort and convenience – it is to make office work, teaching and schoolwork as productive as possible. The indoor environmental conditions should therefore be optimised for cognition because it is the monetary value of the cognitive activities performed in these buildings that pays for the space heating and cooling. Maximising the comfort and convenience of the occupants of these buildings are secondary goals. Thermostats must be set with this in mind.



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Comfort and cognition

It is widely assumed that thermal conditions for cognitive performance will be optimised if subjective thermal comfort is achieved. This is the economic justification for the energy conservation made possible by adopting the Adaptive Thermal Comfort (ATC) rules of thumb that predict acceptable indoor temperatures from a knowledge of outdoor temperature alone. They have been proposed in many current Standards as an alternative to rational models of physiological heat balance and they suggest that higher indoor temperatures are acceptable when it is warm outdoors. A climate-chamber experiment reported by Wyon et al. (1975) exposed subjects to operative temperatures of 18° and 23°C, adjusting the insulation value of their clothing between conditions so that they did not report thermal discomfort in either condition. It was found that their cognitive performance did not differ significantly between the two conditions. For the next 45 years, this finding was taken to support the proposition that cognitive performance must be optimal if no subjective thermal discomfort is experienced. It was assumed without proof that this finding can be extrapolated to temperatures above 23°C. The present authors pointed out that in view of the physiological changes that take place at raised temperatures, this was unlikely to be the case (Wyon and Wargocki, 2014), a reservation that was immediately discounted by the thermal comfort researchers from 6 countries on 3 continents (de Dear et al., 2014) who stated that "we firmly believe (that the evidence supports) the notion that optimal comfort and performance temperatures are broadly aligned" even though their review of 20 years of research on ATC and thermal comfort had found no proof of the assumption.. Two recent climate chamber experiments have now provided evidence that disproves that assumption. First, Lan et al. (2020) showed in a pilot experiment that was carried out in Denmark that the cognitive performance and perceived indoor air quality of 12 subjects were significantly worse at an operative temperature of 27°C than they were at 23°C even though the subjects reported no thermal discomfort at either temperature. Lan et al. (2021) then exposed 36 subjects for 4.5 h to 24, 26 or 28°C in Shanghai in

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hot and humid summer weather in which the average maximum daily temperature was 33°C during the exposures. These subjects remained thermally neutral at all 3 temperatures by adjusting clothing insulation and air velocity. Their self-estimated performance did not change but their objectively measured performance decreased significantly with increasing temperature, by 10 and 6% respectively. The conclusion must be that the absence of thermal discomfort is not a sufficient condition for optimal performance and that the lower the temperature at which thermal neutrality is achieved, the better the resulting cognitive performance will be.

This finding will have to be validated in different seasons, climates and cultures but it seems likely that setting space heating thermostats at the lower bound of the thermal comfort range – which may be well below 23°C if thick clothing is worn and well above this temperature in hot and hot humid areas where clothing is light and sweating is an acceptable and necessary means of maintaining heat balance – will minimise the use of energy for heating and also optimise cognitive performance. The new results cited in the present analysis suggest that in heating mode, thermostats should be set at or below 23°C, or even to as low as 20-21°C in Danish school classrooms in winter (Vorre et al. 2021). A meta-analysis of published experimental results shows that this will improve the performance of schoolwork by up to 20% (Wargocki et al. 2019) and an analysis of ten million end-of-year national examination results in the USA has now confirmed that reducing the mean classroom temperature over a school year will increase learning (Goodman et al. 2018). A recently published experiment that is discussed below in the context of space cooling (Fan et al. 2019) indicates that when maintaining cognitive performance is the goal, thermostats should not be set to above 26°C even in hot and humid areas where still warmer temperatures are traditionally and subjectively regarded as acceptable. If these rules of thumb are followed, no Jevons rebound in energy use will occur following future increases in the energy efficiency of space heating, and no downward trend in clothing insulation values will occur. Using productivity as the criterion for optimising thermostat settings in this way need not result in thermal discomfort: Yamamoto et al. (2010) pointed out that until 1965, the summer thermal comfort zone recommended by the ASHVE Guide that preceded ASHRAE Standard 55 was 24-27°C while the winter thermal comfort zone was 17-22°C. It was always assumed that clothing would be adjusted according to outdoor conditions and that local air

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velocity would be raised when appropriate, e.g., by ceiling fans or table fans, as is assumed when the ATC rules of thumb are applied to optimise thermostat settings for thermal comfort rather than cognitive performance.

Clothing insulation for non-sweating sedentary work

Thick clothing reduces the range of metabolic rates compatible with thermal comfort. It was argued above that it is for this reason that thin clothing is preferred for leisure activities in the home. However, wearing thick clothing during sedentary work can be an advantage, because it ensures that the quite small variations in metabolic rate that can be achieved while sedentary, such as sitting straight or slumping in a chair, are better able to adjust metabolic rate, making it easier to remain in thermal comfort. This is another reason for setting thermostats in schools and offices (and in dwellings where office work is being performed) to temperatures low enough to encourage the wearing of thick clothing. This appears to be the case even at operative temperatures well below 20°C: Jiang et al. (2018) showed that a Mean Thermal Vote (MTV) of -1.4, between cool and slightly cool, was ideal for cognitive performance in some poorly heated classrooms in China, in which unusually thick clothing was being worn – the children's performance was found to be optimal at 14°C. However, while this extreme example supports the general conclusions set out above, WHO guidelines (2018) recommend that to reduce respiratory infections, indoor temperatures should not be lower than 18°C.

Implications for space cooling

Cognitive performance will be maximised if space cooling is operated to ensure that office or classroom temperatures are close to the lower bound of the thermal comfort range, while energy conservation in space cooling will be maximised if temperatures are close to the upper bound. In resolving this conflict between two important facility-management goals it should be recalled once again that investment in the building and operation of schools and offices is justified by how well they contribute to ensuring that office work, teaching and schoolwork are as productive as possible, not by how much energy can be saved while keeping the occupants thermally comfortable. The total cost of heating, cooling and air conditioning per unit of floor area is usually at least two orders of magnitude (100 times) less than that of the recruitment, training, equipment, salary, health insurance, sick leave, vacation and pensions of those occupying the floor space (Woods 1989, Wargocki et al. 2006), and there are many ways of reducing daytime temperatures that do not require active cooling, such as night-time cooling, cross-ventilation, drapes, blinds and window opening when appropriate. However, if active cooling is used, additional energy is required for keeping indoor temperatures closer to the lower bound of the thermal comfort zone than to the upper bound. The lower bound of operative temperature will not be as low as 23°C if clothing insulation values are very low, as they usually are when outdoor temperatures are very high, if activity levels are low and both clothing and skin are damp with sweat following exercise or exposure to hot outdoor conditions, or if air velocity is increased. The measured cognitive performance (accuracy in a Tsai-Partington test) of heat-acclimatised subjects in the hot-humid region of Changsha in China was much better at 26°C than at 30°, 33° or 37°C, even though they found 33°C thermally acceptable and did not report feeling hot below 37°C (Fan et al. 2019). The Jevons Paradox predicts that some of the cost savings due to improvements in the energy efficiency of active space cooling will be used to reduce room temperatures still further and that this will increase energy use. In residential buildings, this would increase total costs, but in school and office buildings, investing some of these cost savings in reducing temperatures to increase productivity is economically justified from a national economic standpoint, as any increase in the energy used for space cooling in school and office buildings will pay for itself.

Conclusions

- The absence of subjective thermal discomfort does not ensure that cognitive performance will be optimal.
- The physiological changes that allow subjective thermal comfort to be achieved above thermal neutrality have the effect of reducing group average cognitive performance.
- The full economic benefit of improving the energy-efficiency of space heating and cooling in school and office buildings will only be achieved if thermostats are set at the lower end of the range of temperatures at which thermal comfort can be achieved.
- This will optimize group average cognitive performance while ensuring that there will then be no "Jevons rebound" in the energy used for heating.
- Any Jevons rebound in the energy used for cooling will be cost-effective because it will improve group average cognitive performance. ■

Acknowledgements

The preparation of this paper was supported by RealDania and the Bjarne Saxhofs Foundation.

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