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Analysis of human interactions together with human-body exergy consumption rate

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Abstract
These days research on occupant behaviour is increasing. Nevertheless, still less is known about the effect of interactions on the occupants themselves. On the one hand, knowing such effects would permit conclusions regarding the purpose of behaviour. On the other hand, this would allow a more careful design of interaction opportunities, which fulfil the occupants' desire for comfortable conditions without posing a danger to their health. This paper describes the analysis of data deriving from field measurements in a student dormitory in Tokyo, Japan. The focus was on the effect of the interaction with the window on the Human-Body Exergy-Consumption (HBx-) rate of the occupant themselves. In conclusion, with respect to thermal conditions, occupant behaviour aims at an optimum rate of exergy consumption, being in congruence with the need to consume as little exergy as possible, but at the same time being able to discard as much of the generated entropy as possible.

Keywords:
Adaptive comfort, field study, exergy consumption, neutral temperature, interaction

1 Introduction

In the recent past, searching for a way to combat global warming towards a sustainable future, the role of the occupant is highlighted more and more both by scientific papers (Lucy and Meisegeier, 2008, Schweiker and Shukuya, 2010) and common articles in the news press (Gill-Austern, 2008; Williams, 2008) especially in relation to the way thermal comfort is provided.

Occupant behaviour is consequently set in relation to thermal aspects of the built environment, such as indoor/ outdoor temperature (Andersen et al. 2009, Haldi and Robinson, 2009). These approaches take the occupant as a sort of "black-box" the behaviour is a result of the input variable.

Schweiker and Shukuya (2010) investigated in addition to these physical factors the influence of factors such as preference or thermal background on the choice to use an air-conditioning unit and found their statistically significant influence. Rijal et al. (2008) investigated the relationship between the state of windows, fans, and doors with respect to thermal comfort. Compared to the first mentioned approach, these approaches try to explain the behaviour by not directly measurable variables.

This paper is following the second approach, thus based on another computed value – the human body exergy consumption (HBx-) rate. As found by previous studies, a lower HBx-rate leads to a higher thermal comfort sensation (Saito and Shukuya 2001, Simone et al. 2011, Schweiker and Shukuya 2012). Therefore, the hypothesis of the relationship between occupant behaviour and HBx-rate is that the human behaviour aims for conditions leading to a lower HBx-rate.

The main distinctiveness of exergy analysis to energy analysis is that it considers the qualitative aspect of energy as a quantity to be calculated, e.g. energy, which is entirely convertible into other types of energy, is exactly exergy, i.e. the highest valued energy such as electricity. Energy, which has a very limited convertibility potential, such as thermal energy close to room air temperature, is low valued energy. Due to such characteristics, the exergy analysis is useful to have a clearer look at sustainability, because it enables us to supply high quality, where high quality is really needed and low quality wherever possible. In such a way, its application assures an optimal usage of the existing resources. With respect to the human body exergy consumption rate, this approach is meaningful for the following reasons: (1) the comparison of different qualities of energy is easy, so that the exergy consumption of the human body can be compared directly with that of the building system, (2) one can show the process of exergy consumption within the human body and thereby achieve a much more detailed knowledge of differences between various environmental conditions

2 Methodologies

2.1 Data collection through field study in international student dormitory

The data base used for this analysis was derived through a physical measurement, which was conducted during summer 2007 and winter 2007/08 within the setting of a student dormitory opened in 1989 in Tokyo area, which is a 5-storied building with 320 identical single rooms and made of concrete with little thermal insulation and single glazed windows. For a detailed description, refer to Schweiker and Shukuya (2009). The single rooms of 15m^2 each including the bathroom are oriented to east, south or west. Each room has one door facing to the corridor and one window on the opposite side, and is equipped with one air-conditioning unit. The residents are free to use electrical fans or other measures to keep their rooms as comfortable as possible without using the air-conditioning unit.

All of the residents are foreign students originating from countries other than Japan. The students who agreed to participate in our measurement came from 27 countries from all continents, with the majority from Europe and Asia. The students arrive either in April or October and the period the students are allowed to live in the dormitory is limited to two years, i.e. most students came to Japan within three and twenty months before the measurement.

For this investigation, 39 students in winter and 34 students in summer who agreed to participate in this survey were invited to a short interview during which they were asked in more detail about their actual behaviour and strategies to keep their room comfortable in summer or in winter. Afterwards they received two sensors: one wireless sensor collecting temperature and humidity values; and the other one, which can indicate if the window is open or closed. In order to prevent a disturbance of privacy, these students were asked to install those sensors themselves.

The room air temperature and humidity values of the student's rooms were collected at a two minute interval from the end of June till the mid of August and from the mid of January till the end of February, respectively. The data of three students in winter and four students in summer had to be excluded from the analyses presented in this paper due to problems with the sensors or missing data. During above named measurement periods, the outdoor temperature, humidity, air current and solar radiation were also measured.

2.2 The calculation of HBx-rate

For this analysis the existing FORTRAN-algorithm (Asada et al. 2008) to calculate the HBx-rate based on the two-node model presented by Gagge et al. (1986) was rewritten into the language used by the program R (R Development Core Team, 2008). This eased the usability and opened up the possibility to use the output of the HBx-rate calculation further in R and through the R-plugin in SPSS.
As input variables for the calculation of the HBx-rate are the following 8 parameters required: (1) outdoor air temperature, $T_{a\text{-}out}$, (2) outdoor air relative humidity, $H_{a\text{-}out}$, (3) indoor air temperature, T_{in}, (4) mean radiant temperature, T_{rad}, (5) indoor air relative humidity, H_{in}, (6) air velocity, A_{in}, (7) metabolic rate, MET, and (8) clothing level, CLO (Shukuya et al. 2010, Simone et al. 2011).

Variables 1 to 3 and 5 could be taken directly from the measurements. Globe temperature and air-current velocity were not measured in order to keep the disturbance due to the measurement devices at minimum. Therefore, T_{rad} was assumed to be equal to the air temperature. A_{in} was assumed to be less than 0 m/s for the situation of a closed window and 0.1 m/s for an opened window since the measured air velocity for those situations in the reference room was similar. The body posture was assumed to be sedentary in the middle of the room. The clothing level was assumed to be 0.6 CLO for the summer period and 1.0 CLO for the winter period. These assumptions could lead to less accurate results, but if a higher accuracy is to be sought, the occupants normal behaviour and privacy could be disturbed by various instruments for measurement, so that it is necessary for us to establish a method to measure in-situ environmental conditions with fewer instruments.

The data obtained from the field measurement was analysed according to the interaction of the occupants with their window. For each interaction the physical conditions (room and outdoor air temperature and humidity) were written into a second database in 5-minute intervals from 30 minutes before the interaction until 30 minutes after the interaction.

For all conditions contained in this second database, the HBx-rate was calculated.

3 Results and discussion

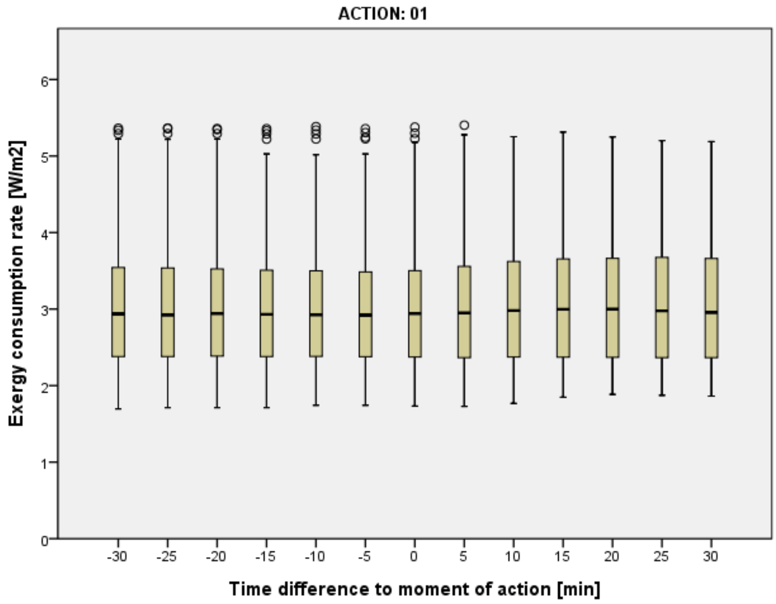
As shown in Table 1, in total 1368 closing interactions and 1375 opening interaction were found in the collected data.

	Opening window	Closing window
Summer	638	643
Winter	730	732
Total	1368	1375

Table 1. Number of actions analysed

Figure 1 summarizes some statistics of the calculated HBx-rates for each of the time steps considered (0=time of interaction) by means of so-called box-plots. The coloured box contains 50% all of values, i.e. the lower edge is the value of the 1st quartile and the upper one of the 3rd quartile of the data. The black bar within each box shows the mean value. The horizontal lines at the upper and lower end of the vertical line – the "whiskers" – are drawn 1.5 times the distance between mean and quartile. For the case that there does not exist such value in the data, the line is drawn at the maximum/ minimum value of the data. All values above/below the whiskers are regarded as outliers and marked with circles.

Looking at Figure 1, there is a huge range of HBx-rates at each timestep. This range looks rather stable before the moment of interaction and then decreases afterwards. This is in particular true for the action of closing the window (action 10 from open (1) to closed (0)).



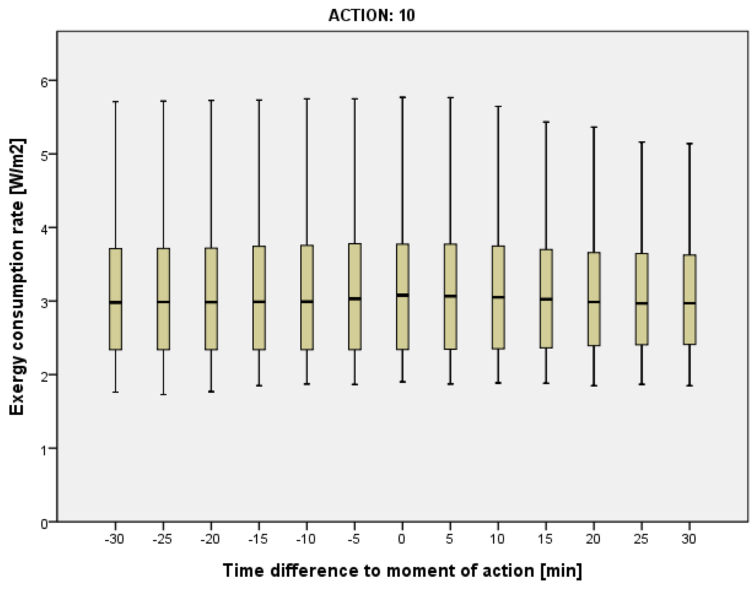


Fig. 1. Distribution of exergy consumed before and after interaction of opening (top) and closing (bottom) the window.

Figure 2 shows only the mean of the HBx-rate for each timestep. It can be clearly seen, that there is a change in the tendency before and after the moment of interaction.

Before the action of opening a window (action 01), the HBx-rate decreases with a sharp increase afterwards. The opposite can be observed for the action of closing a window. Here the HBx-rate increases before the moment of interaction and decreases afterwards. Even though this happens within a very small range of mean HBx-rate (3.00 to 3.12), the action leads to a reversed tendency with respect to the change of HBx-rate.

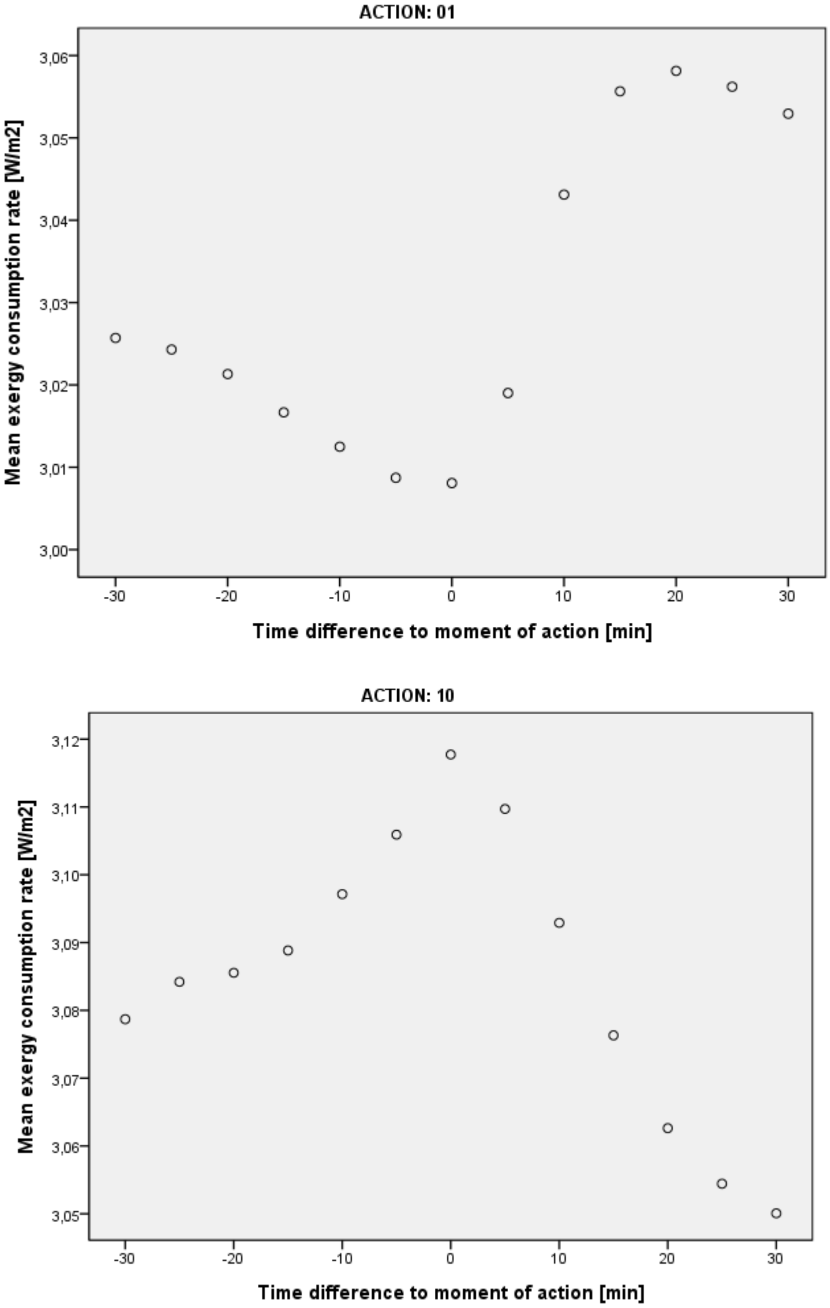


Fig. 2. Mean value of exergy consumed before and after interaction of opening (top) and closing (bottom) the window.

The data was then separated into those deriving from the summer and those coming from the winter measurement in order to analyse the effect of an interaction in a more differentiated way. As shown in Figure 5 and due to the minor differences between indoor and outdoor conditions in summer compared to winter, the change in HBx-rate is much smaller in summer. In addition, opposite tendencies can be observed in summer and winter. In summer, opening the window leads to a decreased HBx-rate, while closing the window to an increased one. In winter, opening the window leads to an increased HBx-rate, while closing the window decreases it.

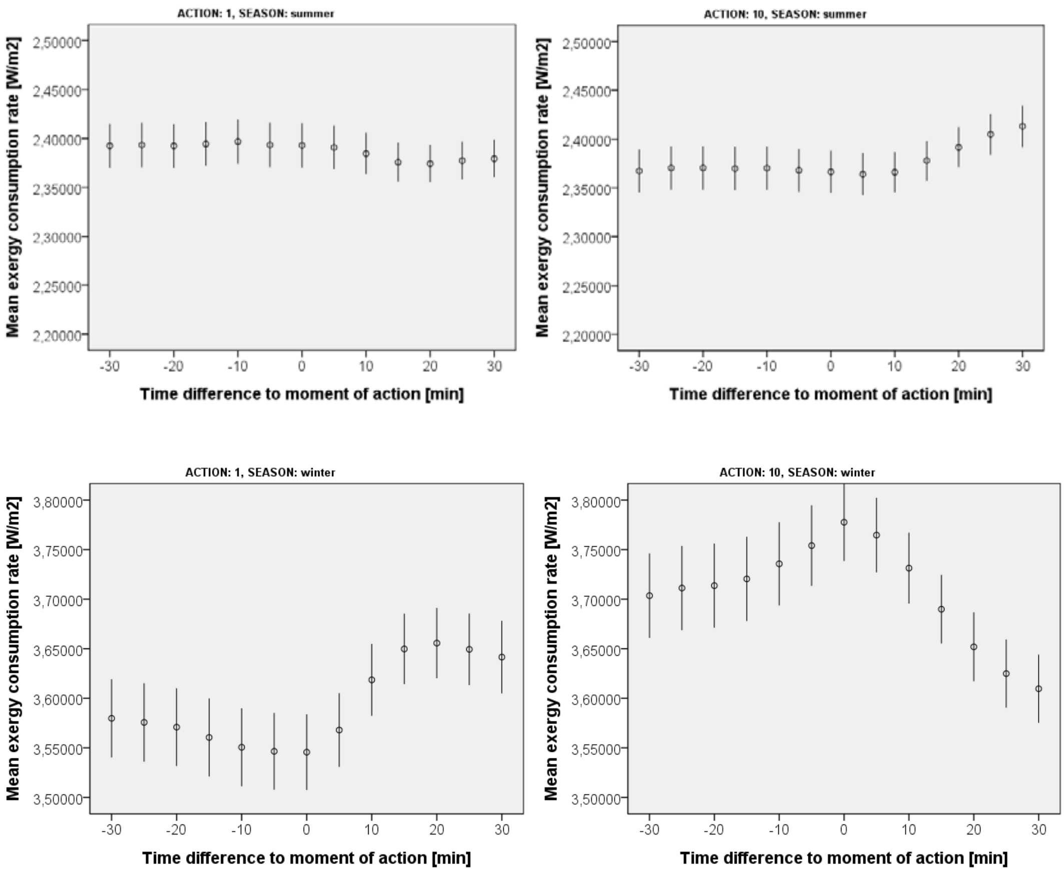


Fig. 3. Mean exergy consumption rate before and after moment of interaction together with their 95% confidence intervals for opening (left) and closing (right) the window in summer (top) and winter (bottom).

At a first sight, such contradictory tendencies look rather inconsistent with the hypothesis stated in the introduction. Nevertheless, the results suggest that there is a rather confined range of HBx-rate regarded as an optimum. Interactions would then occur in order to keep the rate within this range. Such finding is consistent with Schweiker and Shukuya (2007) who found that an action is likely to occur once the HBx-rate of the occupant enters the range of HBx-rates, this occupant was used to during the childhood. Therefore it would be interesting for a future study to look at the individual differences and their relationship to the HBx-rate at the moment of interaction.

Despite these promising results, it remains unclear, whether the change of state leads to a change of HBx-rate or the tendency of the HBx-rate before the interaction leads to the change of state. This needs to be investigated further with future studies.

5 Conclusions

Data from a field measurement in a student dormitory in Tokyo/ Japan was analysed according to the moments of an interaction of the occupant with a window. For the periods of 30 minutes before and after these interactions, the human body exergy consumption rate was calculated. In such manner 2743 interactions were analysed and led to the following findings:

- The range of HBx-rates decreases after an interaction.
- In summer, the mean HBx-rate slightly decreases after an opening action and increases after an closing action. In winter, this is the opposite.

In conclusion, exergy is necessarily consumed to keep the human body working. Entropy is thereby generated and needs to be discharged to the environment. At the same time, an excessive HBx-rate is not appreciated because this would mean that the human body consumes more exergy for thermoregulation than necessary. The findings therefore suggest that an interaction occurs once the HBx-rate is about to leave a certain range of HBx-rates – either to values above or below such range. In order to determine such range and to increase the confidence in such results, it is necessary to conduct further research in this topic.

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