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Thermal Comfort and Productivity – What can the Chair Tell Us?

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Abstract

Past research has suggested that there is a relationship between people who report dissatisfaction with their indoor environment and those that report the office environment to be affecting their productivity. Currently, there is no method to assess productivity objectively. This study develops a new method to measure productivity and thermal comfort of offices' occupants. Mixed-method approach was used to monitor concurrently environmental conditions, office chair movements, self-assessed productivity, and thermal comfort. 3-Axis accelerometers fixed on office chairs were used to monitor occupants' movement while sitting down. The general idea is the more 'twitchy' the chair is, the more productive a person can be. This study involves 6 participants monitored for 4 weeks. Results show that there is a significant relationship between occupants' perceived productivity and occupants' chair movement. Furthermore, the analysis explored the lag effect of environmental variables on perceived productivity, at the time of the survey, one hour prior to the survey, and for a whole day.

Keywords: Thermal Comfort, Productivity, Accelerometer, Office Buildings, Occupants behaviour, Mixed-method approach

1. Introduction

Office evaluations have traditionally been Post Occupancy Evaluation (POE) surveys that assess how satisfied occupiers are with their working environment (Gavin McDougall et al., 2002). Several studies have been conducted to identify relationships between the quality of the office environment and the productivity of its occupiers. In 1995 Leaman found that there is a significant relationship between people who report dissatisfaction with their indoor environment and those that report the office environment to be affecting their productivity (Adrian Leaman, 1995). Although physiological and psychological component also affects office occupiers' productivity, environmental conditions of the office are the only aspect that can be controlled. Environmental variables associated with office's physical conditions include temperature, humidity, air movement, light, noise, and air quality. Today, there is no standard method to assess concurrently thermal comfort, occupiers' personal responds toward the environmental conditions and their productivity.

This study proposes to develop and test a low-cost, non-invasive technique to assess the productivity and thermal comfort of offices' occupants. We are looking to use three axis accelerometers fixed on office chairs to monitor occupants' movements while sitting down. The general idea is the more 'twitchy' the chair is, the more productive a person can be.
The aim of this study is to determine the relationship between thermal comfort and productivity in offices by monitoring the indoor environment and collecting personal responses. The associated objectives are:

- To develop a method to estimate thermal comfort and occupiers' productivity in offices, objectively and subjectively.
- To investigate the relationship between thermal comfort and productivity.

2. Thermal Comfort and Productivity

Most of the previous researches in this area of study are focusing more on a single factor that could affect occupants' performance at work. Up until now, no study has been done to examine the relationships between the whole factors of physical office environment and the occupants' productivity (Kamarulzaman et al., 2011). Two types of thermal comfort approaches can be used to analyse the relationships that the researcher aims to investigate. Both adaptive and predictive model will be used as elaborated by de Dear "*a variable indoor temperature standard can successfully combine features of both static and adaptive models by incorporating behavioural, physiological and psychological modes of thermal adaptation*" (de Dear and Brager, 1998). Therefore, the study will be conducted by comparing the perceived thermal comfort and productivity data collected from the occupants with indoor environment parameters measured by sensors and equipment.

3. Study Design

This paper outline the main study part of the research which lasted for four weeks in July 2016. Office's environmental condition and occupiers' behaviors will be monitored on daily basis during the study using a mixed-method approach. The data collection methods will consist of: a) General and daily questionnaires, b) Environment condition monitoring and c) Personal responses monitoring (chair movement). The six participants in this study are researchers working in an office building at University of Southampton. To measure occupants' thermal comfort, daily questionnaires were based on ASHRAE standard 55-2010, EN ISO 10551:2001, and RP-884 database. Initial surveys were handed out directly to the participants, and afterwards, thermal comfort questionnaire were completed at random times of the day using either a mobile phone application, or internet survey for the participants who did not possess an iPhone. The thermal comfort phone application was developed with a purpose to assist the subjective quantitative data collection.

Applying a mixed-method approach, data were collected using occupant thermal comfort survey in the form of daily questionnaire, and environmental monitoring. Afterwards, data sorting and inferential statistics were carried out using R studio. Due to mixed-method approach, the obtained data have a mixed of continuous and discrete variables. Thus, two different approaches were applied to produce comprehensible data frames which are productivity versus reported thermal comfort level (Discreet-Discreet), and productivity versus environmental variables along with Predictive Mean Votes (PMV) and Linear Acceleration (LA) of the chair (Discrete-Continuous). Kendall's Tau-b were used to find the correlation coefficient with data samples with tied ranks for the first approach while Chi-square test were employed for the latter approach. The lag effect of environmental variables on perceived productivity, at the time of the survey (T0), one hour prior to the survey (T1), and for a whole day (Td) was explored. Finally, variables with high correlation value were chosen and fitted for multiple regression along with productivity.

4. Results

During four weeks or twenty working days, datasets consisting of reported thermal comfort, productivity, selected environmental parameters and chair movement for six people were obtained. The results were processed and separated into three main categories based on the period of the survey (T0, T1, and Td). Indoor environmental parameters including ambient temperature (Ta), radiant temperature (Tr), relative humidity (RH), CO_2 level (CO_2), light level next to the window (Lighting1), light level on the back wall (Lighting2), noise level (noise), along with linear acceleration (LA) were paired with productivity of each occupant.

Table 1 depicts the relationship for each variables and each participant, taken at the time of the survey (T0). The upper value represents correlation coefficient while lower value shows the p-value. Blue colours for certain cells were adapted to represent the coefficient range, the darker the blue means the higher the correlation value. The previous study suggest that the calculated PMV based on ISO 7730 Annex D shows almost no relationship with occupants' productivity, hence it has been excluded from this analysis.

Table 1. Correlation Coefficient and P value at the time of the survey – Main Study

Participants	Ta	RH	CO_2	Lighting1	Lighting2	Tr	Noise	LA
1	-0.22	-0.09	0.04	0.22	0.22	-0.56	-0.13	-0.31
	0.36	0.72	0.86	0.36	0.36	0.06	0.58	0.20
2	0.34	0.02	-0.08	0.02	-0.02	-0.02	0.05	-0.05
	0.14	0.94	0.73	0.94	0.94	0.93	0.83	0.83
3	-0.41	0.69	-0.05	0.05	0.14	-0.32	-0.41	0.14
	0.19	0.03	0.88	0.88	0.66	0.48	0.19	0.66
4	0.30	-0.12	0.14	-0.12	0.12	0.40	-0.14	-0.18
	0.15	0.56	0.50	0.56	0.56	0.08	0.50	0.38
5	0.14	-0.22	-0.34	0.11	0.01	-0.01	0.07	0.09
	0.44	0.24	0.06	0.53	0.94	0.96	0.70	0.64
6	-0.07	0.01	0.14	-0.07	-0.20	0.16	0.14	-0.31
	0.77	0.95	0.51	0.77	0.37	0.54	0.51	0.15

Correlation Coefficient Range	
	0.01-0.20
	0.21-0.40
	0.41-0.60
	0.61-0.80
	0.81-1.00

Table 2 depicts the relationship between occupants' productivity and measured variables one hour prior to the survey (T1). Several blue cells can be spotted from the table, although not all of them have p-value below 0.05.

Table 2. Correlation Coefficient and P value one hour prior to the survey – Main Study

Participants	Ta	RH	CO_2	Lighting1	Lighting2	Tr	Noise	LA
1	-0.18	-0.09	0.18	-0.22	0.04	-0.39	0.04	-0.31
	0.47	0.72	0.47	0.36	0.86	0.19	0.86	0.20
2	0.11	-0.11	0.18	-0.05	0.08	-0.17	-0.02	-0.11
	0.62	0.62	0.44	0.83	0.73	0.52	0.94	0.62
3	-0.32	0.69	0.05	0.32	0.14	-0.32	-0.41	0.41
	0.31	0.03	0.88	0.31	0.66	0.48	0.19	0.19
4	0.20	-0.12	0.12	0.04	0.16	0.40	-0.18	-0.31
	0.33	0.56	0.56	0.85	0.44	0.08	0.38	0.12
5	0.19	-0.24	-0.57	0.01	-0.01	-0.07	0.22	0.14
	0.31	0.19	0.00	0.94	0.94	0.73	0.24	0.44
6	-0.12	0.01	0.09	0.17	-0.17	0.33	0.20	-0.47
	0.59	0.95	0.68	0.44	0.44	0.19	0.37	0.03

Correlation Coefficient Range	
	0.01-0.20
	0.21-0.40
	0.41-0.60
	0.61-0.80
	0.81-1.00

Table 3 depicts the same correlation variables as two previous tables, but it records the summary for the whole day of the survey (Td). Overall, it can be seen than this period of times shows the most significant correlation values over the three time periods although p-values for all variables are quite high.

Table 3. Correlation Coefficient and P value for the whole day – Main Study

Participants	Ta	RH	CO_2	Lighting1	Lighting2	Tr	Noise	LA
1	-0.09	-0.09	0.54	0.40	0.13	-0.40	0.09	-0.04
	0.72	0.72	0.03	0.10	0.58	0.15	0.72	0.86
2	-0.05	0.02	0.30	-0.14	-0.14	-0.15	0.05	-0.21
	0.83	0.94	0.18	0.53	0.53	0.56	0.83	0.36
3	-0.60	0.69	-0.23	-0.23	-0.41	0.00	-0.32	-0.41
	0.06	0.03	0.47	0.47	0.19	1.00	0.31	0.19
4	0.10	0.02	0.04	-0.18	-0.12	0.27	-0.22	-0.16
	0.63	0.92	0.85	0.38	0.56	0.22	0.29	0.44
5	0.30	-0.33	-0.20	0.09	0.19	0.02	-0.03	-0.14
	0.10	0.07	0.28	0.64	0.31	0.93	0.88	0.44
6	-0.01	0.01	-0.07	-0.04	-0.17	0.04	0.12	-0.30
	0.95	0.95	0.77	0.86	0.44	0.88	0.59	0.17

Correlation Coefficient Range	
	0.01-0.20
	0.21-0.40
	0.41-0.60
	0.61-0.80
	0.81-1.00

Given the information from the table 1, 2, and 3, independent variables have quite high p-value. It means we accept the null hypothesis and can't conclude that a significant difference exists, even though the correlation coefficient is significant. Relative Humidity (RH) for Participant 3 display strong correlations with productivity in all three tables, along with CO_2 level observed for a whole day. Meanwhile, the other variables only show a moderate correlation coefficient. In the second part of the analysis, scatterplots were used to explore the relationship between Ta, RH, CO_2 level, lighting level, Tr, noise level, and linear acceleration with productivity. Results show that he only significant relationship was between LA and productivity.

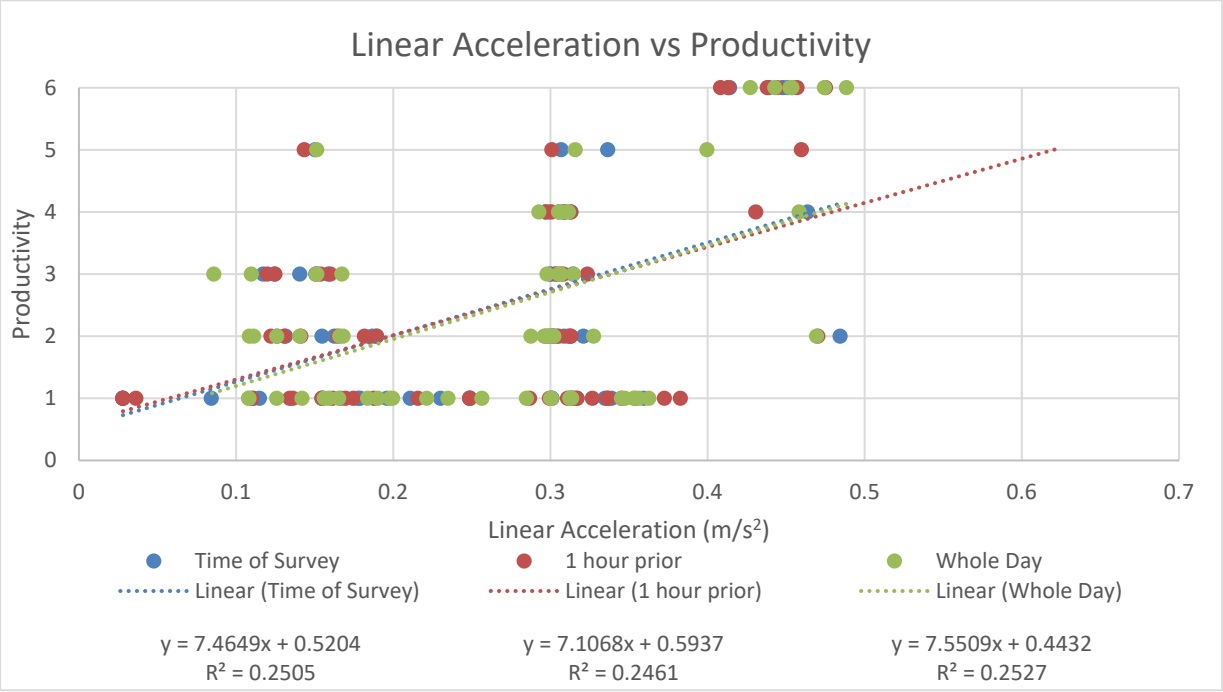

Figure 1. Linear Acceleration vs Productivity during Main Study

Figure 1 depict the average linear acceleration from all occupants plotted with their productivity level. Observation during time of the survey and for the whole day shows that linear acceleration has relationship with linear acceleration. Although both have relatively low R^2 value, **linear acceleration has a tendency to increase along with increased productivity.**

Multiple regressions for time periods (T0, T1, and Td) were undertaken. Results show that only chair movement was a significant factor of productivity. To follow this analysis, the following equation were derived with productivity (Prod) as dependant variable and chair's linear acceleration (LA) as independent variable:
T0: Prod = 6.95 LA + 0.64
T1: Prod = 6.95 LA + 0.64
Td: Prod = 7.35 LA + 0.48

Heat Map method was used to explore the relationship between perceived thermal comfort and perceived productivity (Discreet-Discreet) from daily questionnaire. Higher value of productivity means participants were more productive, while the thermal sensation ranged from -3 (cold) to +3 (hot) with 0 value as neutral. Figure 2 through 7 illustrate the relationship of perceived thermal comfort and productivity for each respective participant. As depicted in Figure 2, participant 1 felt more productive most of the time when they felt neutral. Figure 3 and 7 shows that participant 2 and 6 felt less productive when they felt warm. In contrary, participant 3 felt more productive when they felt warm, as shown in Figure 4. Meanwhile, Figure 4, 5, and 6 shows a scattered data.

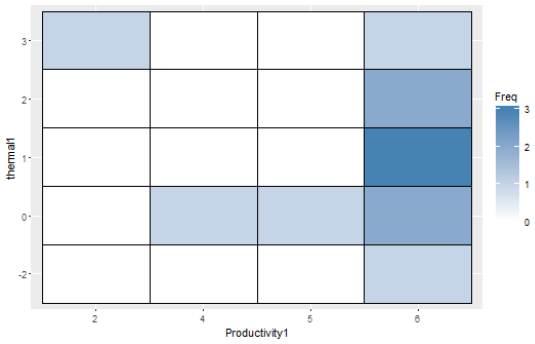

Figure 2. Thermal Comfort vs Productivity Participant 1

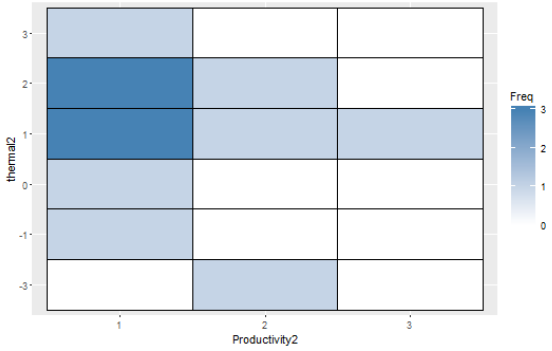

Figure 3. Thermal Comfort vs Productivity Participant 2

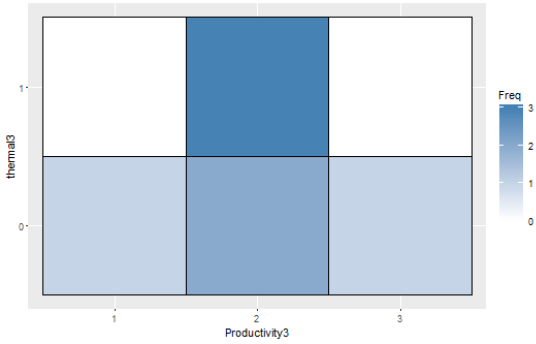

Figure 4. Thermal Comfort vs Productivity Participant 3

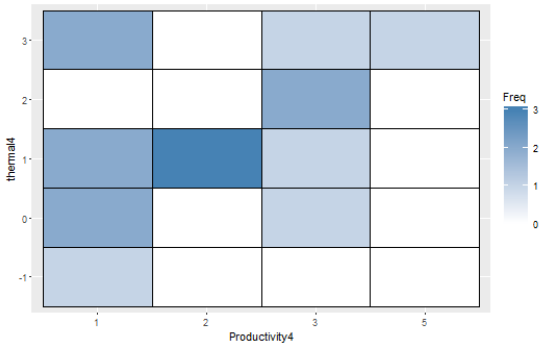

Figure 5. Thermal Comfort vs Productivity Participant 4

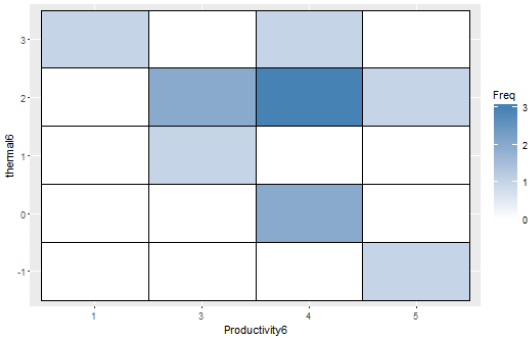

Figure 6. Thermal Comfort vs Productivity Participant 5

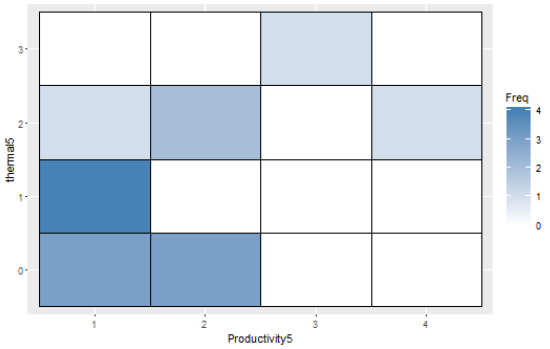

Figure 7. Thermal Comfort vs Productivity Participant 6

From the results, we observed 4 types of people: 1) People who are more productive when they felt neutral; 2) People who are more productive when they felt more warm; 3) People who are more productive when they felt more cold; 4) People with no correlation between perceived thermal sensation and productivity level.

5. Conclusion

Following a mixed-method approach, participants' chair movements was found to be a significant factor to reported productivity, while the other variables do not show any significant results. Chair movements gave a positive correlation with productivity, in which the more the chair 'twitch', the more productive it's occupier might be. We also observed three types of people who behaves differently according to their reported thermal comfort level. However, this study was limited by the number of participant and limited time of data collection. Improvements for further study may include: 1) Comparing productivity from previous day to have a baseline for each participant regarding their own perceived productivity level; 2) Defining productivity in more depth; 3) Basing questionnaire not on the exact moment, but one hour prior to the survey because the exact moment could not represent what actually happening at the time of the survey.

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