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The effect of indoor thermal comfort on visual search task performances in a personal learning environment

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Abstract: This study examined the effect of perceived indoor thermal comfort of a personal learning environment on students' performances of the visual search task. To do this, 11 participants who attended a high school completed the scale of indoor thermal comfort in the simulated learning environment and they performed the visual search task which reflects selective attention. As a result, there was a strong negative correlation between indoor thermal comfort and visual search task performance regardless of task difficulty. This was different from the common sense view that comfortable environments improve occupant's performances. While this result could have been affected by students' arousal level or perceived sensitivity to the environments, these variables didn't appear to significantly influence the inverse relationship between indoor thermal comfort and visual search task performance. These findings could potentially be used to shape an optimal thermal learning environment in order to improve learner's learning performance.

Keywords: Indoor Thermal Comfort, Visual Search Task Performance, Perceived Thermal Sensitivity, Arousal Level, Learning Environment

1. Introduction

An individual's performance on learning tasks is affected not only by internal factors, such as individual capability, but also by external environmental factors. In light of this, some studies examined the impact of basic thermal environment (e.g., coldness and heat) on performance [1-4]. According to Seppänen and Fisk (2006), individuals' activity levels are highest when the indoor temperature is 21.6℃, while activity level falls at temperatures below and above that [3]. Choi and Chun (2009) examined attentional level at 20℃ and 23℃ and found that in general, an indoor temperature of 23℃ provides an environment more conducive to concentration [1]. However, Tham and Willem (2010) used indoor temperature conditions at 20℃, 23℃, and 26℃ and found that, unlike in the previous study by Choi and Chun (2009), the difference in concentration levels at 20℃ and 23℃ was not statistically significant, whereas 26℃ provided the optimal environment for concentration, as measured by faster reaction times and reduced error rates [4]. On the other hand, Kim et al. (1996) studied participants' performance on a word-combination-task at 23℃ and 26℃ and found that the performance difference at these two temperatures was not statistically significant [2].

However, the aforementioned studies only changed indoor temperature as a thermal environment condition to see how it affected performance. While each study had different restrictions on performance type, even similar performance types at different indoor temperatures were inconsistent across the studies. This outcome indicates that in composing thermal environment, relative humidity, air velocity, and mean radiation temperature must be considered along with indoor temperature. Thus, even if previous studies used the same indoor temperature, the thermal environments would still differ [5]. Therefore, the four physical elements of thermal environment (indoor temperature, relative humidity, air velocity, and mean radiation temperature) suggested by Fanger (1970) all must be taken into account when examining the basic thermal environment conditions that affect performance [6]. Based on the use of attention tasks as a performance measure in previous studies, Kim et al. (2011a) employed a visual search task, which reflects the mechanisms of selective attention, and induced changes in thermal environment characteristics by using an air conditioner; they then analyzed the impact of these characteristics on performance [5]. They found that an increase in relative humidity, a decrease in air velocity, and an increase in mean radiation temperature resulted in enhanced performance in the visual search task. These findings suggest that the inconsistency in performance results in the previous studies have been due to the failure to control for the other physical elements—with the exception of indoor temperature—comprising thermal environment, which might have a greater impact on performance than indoor temperature itself [7-8].

Kim, Min, Min & Kim (2011) also suggested that even if predicted mean votes (PMVs hereafter), which take into account the physical elements of thermal environment suggested by Fanger (1970), are all consistent—that is, the thermal environments are all controlled to the same degree—the psychological and physiological traits that arise due to those elements may differ [9-11]. In other words, even if the other physical elements of thermal environments, including indoor temperature, are controlled to the same level, the human-environment interaction, such as how a person perceives the current thermal environment, would have a bigger impact on performance [12-13].

Thus, indoor thermal comfort can be considered a by-product of the human-environment interaction [14-15]. Many studies have analyzed the elements of comfortable environments to improve educational environments under the expectation that a comfortable learning environment (e.g., classrooms) would enhance the performance of the students studying in those environments [16-19]. Lee & Lee (1986) proposed that 22℃–25.2℃ in summer and 14.7℃–18.1℃ in winter are the most comfortable temperature ranges for learning environments [17], while Ahn et al. (2003) argued that floor panel heating is more desirable than an air heating system for a comfortable thermal environment, especially in winter [16]. In addition, Chung et al. (1997) noted that humidity adjustment in summer is important in creating a comfortable thermal environment [19] and Cheong et al. (2009) found that, even in winter, humidity adjustment is important and that an appropriate level of ventilation is necessary for a comfortable thermal environment [18]. However, aside from Chung et al. (1997), these other studies assessed comfort sensation votes (CSVs) based on PMV indicators [19]. According to Kim, Min & Kim (2013), PMV indicators do not show a statistically significant correlation with CSVs—the level of comfort subjectively assessed by people—essentially rendering the use of PMV indicators to measure comfort sensation inappropriate [20]. Thus, it can be interpreted that previous studies did not apply comfort sensation as a by-product of the human-environment interaction. In addition, these studies have a limitation in that they failed to directly examine the changes in students' performance in comfortable environments when those environments were directly created.

The aim of this study was to examine the effect of perceived indoor thermal comfort on the performance of participants' visual search task. To do this, the present study sought to directly examine the correlation and regression between comfort sensation and learning task performance by assessing participants' learning task performance in a controlled thermal environment. To this end, we selected high school students and asked them to perform the visual search task used in the study by Kim et al. (2011) in a simulated learning environment [5]. We also assessed the comfort sensation of the indoor thermal environment, based on the participants' CSVs. Furthermore, based on the findings of Kim et al. (2011)—that increases in participants' sensitivity to the external environment could decrease learning task performance—we assessed perceived thermal sensitivity (PTS) as an extraneous variable in the impact of comfort sensation on learning task performance [12]. Considering that PTS can be calculated as an absolute value in the difference between actual indoor temperature and participants' perceived temperature, participants were asked to estimate the current room temperature. Furthermore, based on the findings of Choi et al. (2013) that the arousal level of individuals also affects performance, this study assessed the arousal level of participants by using a Likert scale, with 1 indicating "relaxed" and 5 indicating "aroused." [21]

2. Methods

2.1. Participants

Eleven female high school students participated in the study; their average age was 17.82 years (SD = 0.60). All participants had normal vision or corrected to normal vision. Participants stayed in a waiting room with the same temperature as the initial temperature of the laboratory for about 10 minutes before the experiment, and the amount of clothing for the participants was set at 0.7clo (refer to ISO 7730 Annex C: Estimation of thermal insulation of clothing ensembles) [22]. Furthermore, the visual search task that the participants were asked to perform required them to sit in a chair and search for a pre-determined stimuli, which they selected by pressing one of two keys, so their activity level was set at 1.0 met (see Figure 1) [23].

Figure 1. *Example of experimental scene.*

2.2. Stimulus and Apparatus

Stimuli for the experiment were equivalent to those used in the visual search task of Kim et al. (2011) [5]. The task was performed on the E-Prime 1.2 Program. The program was run on a 17-inch LCD monitor with a 1027 × 768 resolution at 75 Hz. Participants were asked to sit 70 cm away from the monitor, and the stimuli were presented in black against a grey background (RGB 128 × 128 × 128, gray scale). The experimental stimuli, as in Figure 2, were 1.2° × 1.2° squares with holes sized at 0.6° in the middle of one of the sides. The targets were squares with a hole on the left or the right side, and the distracters were squares with a hole on the top or bottom. Each stimulus randomly changed its location within a 12° × 8.5° range, and the number of stimuli was randomly set at 4, 8, or 12. The targets in the stimuli examples in Figure 2 are squares with the holes on the left side, and the number of stimuli is 4 (low difficulty level), 8 (medium difficulty level), and 12 (high difficulty level).

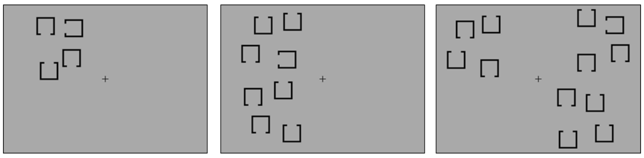

Figure 2. *Examples of the experimental stimulus (From left, task difficulty is low, medium and high).*

2.3. Procedures

The experiment lasted for about 50 minutes for each participant and took place in a non-air-conditioned room during summer. As can be seen in Figure 3, the experiment was carried out in eight blocks, and for each block contained 72 stimuli. Between blocks were 30 seconds of recess time. The participants were asked to rate the level of indoor thermal comfort by using a Likert scale with 1 indicating "not comfortable at all" and 7 indicating "very comfortable."

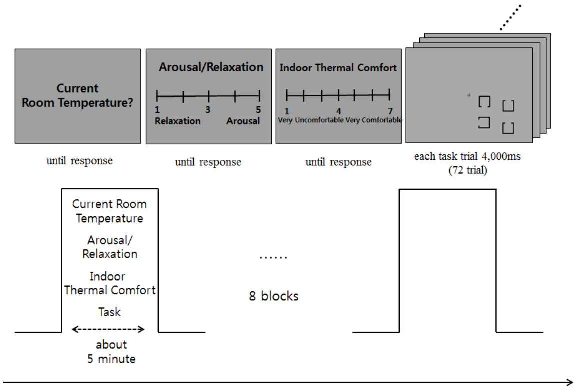

Figure 3. *Experimental procedures.*

Stimuli in each block were provided as follows: after the participants rated the level of indoor thermal comfort, a "+" sign was displayed for 1,000ms, and then the experimental stimuli were displayed for a maximum of 4,000ms. On each task grid, participants were asked to press either "1" or "2" on the keyboard when they found the target, "1" if the target was a square with a hole on the left side and "2" if the target was a square with a hole on the right side. If participants did not react within 4,000ms, then the next stimulus was presented. The total number of task trials was 576 (8 blocks × 72 stimuli for each block), and the order of stimuli in each block was provided wirelessly.

2.4. Experimental Design and Analysis

To examine the impact of perceived indoor thermal environment in a simulated learning environment on students' visual search task performance, a correlation analysis of indoor thermal comfort and the reaction time for each difficulty level of the visual search task was undertaken. Then, with indoor thermal comfort as the predictor variable and reaction time for each difficulty level of the visual search task as the criterion variable, a simple regression analysis was conducted. Furthermore, this study also considered the relationship between participants' arousal level and PTS and their reaction time in the visual search task via correlation and regression analyses, to exclude the impact of extraneous variables [24].

3. Results

First, we carried out a correlation analysis of indoor thermal comfort and reaction time for each difficulty level of the visual search task. The results are shown in Table 2 and were as follows: reaction time at each level of task difficulty - high (number of distracters = 11), medium (distracters = 7), and low (distracters = 3) - was positively correlated to indoor thermal comfort with the correlation coefficient at .308, .328, and .390, respectively. In other words, reaction time tended to be longer in an environment with higher indoor thermal comfort than in an environment with lower indoor thermal comfort.

Table 1. *Descriptive statistics of ITC and RTs.*

Variables		**Mean (SD)**	**N**
ITC		4.159 (0.725)	88
Arousal Level		3.614 (0.863)	
PTS		1.728(1.265)	
RTs (ms)	High Difficulty	645.242 (86.419)	
	Medium Difficulty	881.078 (138.666)	
	Low Difficulty	1,050.519 (190.633)	

Note. ITC = Indoor Thermal Comfort, PTS = Perceived Thermal Sensitivity, RTs = Reaction Times of the Visual Search Task, SD = Standard Deviation

Table 2. *Results of the correlation among ITC, Arousal Level and RTs.*

Variable	**RTs of the Visual Search Task (ms)**		
	High Difficulty	**Medium Difficulty**	**Low Difficulty**
ITC	.308**	.328**	.390**
Arousal Level	-.076	-.049	-.030

**p<.01

We then conducted a regression analysis using reaction time for each level of task difficulty as the criterion variable and indoor thermal comfort as the predictor variable. The findings are indicated in Table 3, and as follows. First, when task difficulty was high, the goodness of fit of the regression model was statistically significant [$F_{(1,86)}$=9.037, $p < .01$], and thus indoor thermal comfort was determined to be a statistically significant variable in predicting reaction time [Beta = .308, t = 3.006, $p < .01$].

Table 3. *Results of regression analysis between ITC and RTs.*

Criterion Variable	Constant B	B	SE	Beta	t	F	R^2 (Adjusted R^2)
High Difficulty	713.446	81.045	26.959	.308	3.006**	9.037**	.095(.085)
Medium Difficulty	620.403	62.676	19.475	.328	3.218**	10.357**	.107(.097)
Low Difficulty	452.020	45.458	11.830	.390	3.927***	15.421***	.152(.142)

**p<.01, ***p<.001

Note. B=Regression Coefficient, SE=Standard Error, Beta=Standardized Regression Coefficient, R^2=R Square.

This finding suggests that every 1 point increase in indoor thermal comfort led to an approximate 81ms increase in reaction time for a task with a high level of difficulty [$Y' = 713.446 + 81.045X$] and that the students' reaction time for a task of high difficulty is 9.5% attributable to indoor thermal comfort.

When task difficulty was medium, the goodness of fit of the regression model was statistically significant [$F_{(1,86)}$=10.357, $p < .01$], and thus indoor thermal comfort was determined to be a statistically significant variable in predicting reaction time [Beta = .328, t = 3.218, $p < .01$]. This finding suggests that every 1 point increase in indoor thermal comfort led to an approximate 62ms increase in reaction time for a task with a medium level of difficulty [$Y' = 620.403 + 62.676X$] and that the students' reaction time for a task of medium difficulty is 10.7% attributable to indoor thermal comfort.

When task difficulty was low, the goodness of fit of the regression model was statistically significant [$F_{(1,86)}$=15.421, $p < .001$], and thus indoor thermal comfort was determined to be a statistically significant variable in predicting reaction time [Beta= .390, t = 3.927, $p < .001$]. This finding suggests that every 1 point increase in indoor thermal comfort led to an approximate 46ms increase in reaction time for a task with a low level of difficulty [$Y' = 452.020 + 46.458X$] and that the students' reaction time for a task of low difficulty is 15.2% attributable to indoor thermal comfort.

Table 4. *Results of the correlation among PTS, RTs and ITC.*

Variable	RTs of the Visual Search Task (ms)			ITC
	High Difficulty	Medium Difficulty	Low Difficulty	
PTS	-.398**	-.428**	-.325**	-.331**

**p<.01

Note. PTS=Perceived Thermal Sensitivity

In order to exclude the influence of the first extraneous variable, arousal level, which could have affected students' visual search task performance, we conducted a correlation analysis between participants' arousal levels and reaction times to the visual search task. The results indicated that, regardless of the level of difficulty, the correlations between reaction time and arousal level were not statistically significant (see Table 2). In other words, the arousal levels of the participants when they were performing the tasks likely did not affect the relationship between participants' perceived indoor thermal comfort and their learning task performance.

In addition, we conducted another correlation analysis between participants' PTS and their reaction times to the visual search tasks to exclude the influence of PTS, the second extraneous variable, which could have affected students' learning task performance. The results indicated that, at all levels of difficulty, the correlations between reaction time and PTS were statistically significant (see Table 4). Following this result, a correlation analysis between PTS and indoor thermal comfort was conducted, and the findings of this revealed that the correlation between these two variables was also statistically significant (see Table 4). This finding may be the result which the extraneous variable PTS affects performing the visual search task rather than that participants' perceived thermal comfort.

Then, we conducted a hierarchical regression analysis with reaction time for each level of difficulty as the criterion variable and indoor thermal comfort and PTS as predictor variables in order to determine whether indoor thermal comfort affected the visual search task performance even when PTS was controlled (see Table 5). Indoor thermal comfort was input into the first stage, and PTS was input into the second stage. For entering the predictor variables, the "Enter" method was used. We found that when task difficulty was high, the goodness of fit of the two-stage regression model was statistically significant [$F_{(2,85)}$=10.205, $p < .001$], and PTS was determined to be a statistically significant variable in predicting reaction time [Beta = -.333, t = -3.223, $p < .01$]. On the other hand, indoor thermal comfort only showed a significant trend with a p-value of .058 [Beta = .198, t = 1.919, p = .058].

When the task difficulty was medium, the goodness of fit of the two-stage regression model was statistically significant [$F_{(2,85)}$=12.141, $p < .001$], and both PTS and indoor thermal comfort were determined to be statistically significant variables in predicting reaction time [PTS: Beta = -.359, t = -3.541, $p < .01$; ITC: Beta = .209, t = 2.061, $p < .05$].

When the task difficulty was low, the goodness of fit of the two-stage regression model was statistically significant [$F_{(2,85)}$=10.289, p <.001], and as with medium task difficulty, both PTS and indoor thermal comfort were determined to be statistically significant variables in predicting reaction time [PTS: Beta = -.219, t = -2.127, $p < .05$; ITC: Beta = .317, t = 3.076, $p < .01$].

Table 5. *Results of regression analysis among ITC, PTS and RTs (step 2).*

Criterion Variable	Predictors	Constant B	B	SE	Beta	t	F	R^2 (Adjusted R^2)
High Difficulty	ITC	920.578	52.073	27.131	.198	1.919	10.205***	.194 (.175)
	PTS		-50.136	15.556	-.333	-3.223**		
Medium Difficulty	ITC	782.962	39.939	19.382	.209	2.061*	12.141***	.222 (.204)
	PTS		-39.347	11.113	-.359	-3.541**		
Low Difficulty	ITC	513.942	37.796	12.289	.317	3.076**	10.289***	.195 (.176)
	PTS		-14.988	7.046	-.219	-2.127*		

*$p<.05$, **$p<.01$, ***$p<.001$

The findings suggest that PTS shared part of the variance with indoor thermal comfort, which explained the performance of participants at different levels of difficulty, while another part could not be fully explained by PTS. In other words, the impact of indoor thermal comfort on the visual search task performance was not reflected solely by the impact of the extraneous variable PTS.

4. Conclusion and Discussion

This study examined the impact of indoor thermal comfort on learning task performance. We selected female high school students and asked them to perform a visual search task in a simulated learning environment, and then analyzed the relationship between participants' perceived comfort level of their learning environment and their reaction time, which was used as an assessment of task performance. We found that, regardless of the task difficulty, participants' perceived indoor thermal comfort showed a positive correlation with reaction time, and indoor thermal comfort had a statistically significant impact on reaction time. This implied that as female students' perceived indoor thermal comfort level increased, their learning task performance decreased; this was the opposite of what was found in previous studies, whose results showed that a comfortable learning environment had a positive impact on students' task performance [16-19].

Why does performance level decrease rather than increase when indoor thermal comfort level - in other words, positive affectiveness - increases? One answer could be that the arousal level of each participant was higher than the arousal level for optimal performance [21]. According to the two-dimensional model of emotion, valence, i.e., comfort and discomfort, forms one axis, with arousal as another axis perpendicular to it. This suggests that the increase in comfort level is separate from any change in arousal level; thus, even if the perceived comfort level of the learning environment increases, it is possible that the impact of arousal on female students' performance is separate from the impact of that. However, we examined the correlation between female students' performance and their arousal level, and discovered that the correlation was not statistically significant. Based on this finding, the explanation that different arousal levels among students caused them to perform poorly during increased indoor thermal comfort is likely not appropriate.

In contrast, Kim et al. (2011) stated that higher PTS could actually contribute to decreases in learning task performance [5]. Considering their findings, it is likely that female students' learning task performance worsened when indoor thermal comfort increased because a higher comfort level tends to be accompanied by a higher thermal sensitivity to the external environment. To test this premise, we included PTS in our analysis of the relationship between indoor thermal comfort and learning task performance to see if there was any correlation between these variables; we found that PTS had statistically significant correlations not only with learning task performance but also with indoor thermal comfort. Following this, we controlled PTS and then examined the sole impact of indoor thermal comfort on learning task performance. The results showed that, even though there was a trend between the two variables when task difficulty was high; thus, indoor thermal comfort still had an impact on learning task performance even after controlling for PTS.

According to the results mentioned above, it is clear that an increase in perceived indoor thermal comfort in a simulated learning environment directly causes poor learning task performance among participants. This outcome supports research done by Kim (2014), who suggested that if students perceived indoor thermal comfort conditions as more unpleasant, their performance might increase [25]. These findings, along with those of Kim, Min & Kim (2012), which showed that a PMV-based physical environment might actually make occupants perceive their environment as more unpleasant, imply that PMV indicators - which we previously evaluated as inappropriate for measuring comfort sensation - could actually be a better method for creating an optimal learning environment [26].

Despite the aforementioned findings, this study was also restricted in that only a small number of female high school students were selected for the experiment, thus making it difficult to generalize the findings. Furthermore, the experiment was conducted during summer in a non-air-conditioned learning environment, which also restricts the scope of the study. As such, in follow-up studies, male high school students must also be selected to examine whether the results differ depending on gender. Furthermore, the range of participants should be expanded to include elementary, middle school, and university students to examine whether similar results can be derived from the same experimental procedure. In addition, the number of participants should be increased so that the results can be better generalized, and the experiment should be conducted in an air-conditioned learning environment to see whether different results are produced depending on the status of air conditioning. Furthermore, the current experiment was conducted on a single-person basis in a simulated setting, so the findings can only be extrapolated to the individual learning environment at home; further extrapolation to a learning environment such as the classroom, where there are many students, can be difficult. As such, follow-up studies must make the necessary adjustments of number of students in one room to examine what kinds of outcomes are derived in a learning environment with many students.

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