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Investigating influence of environmental information on occupants perceived indoor environmental quality: An exploratory study

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Abstract

Under the assumption that information can impact perception, most research on human sensation and satisfaction with indoor environmental quality (IEQ) parameters has been conducted with respondents uninformed about the test conditions. Therefore, researchers know little about the impact of information on perception. These potential effects are increasingly relevant as quantitative information about indoor environments becomes accessible via low-cost, wirelessly connected sensors. In this experimental study, 48 subjects were exposed to varied indoor environmental conditions and provided with different types of environmental information. The subjects' sensation and satisfaction were compared when they were blinded or provided with quantitative information about and/or qualitative ratings of specific parameters. The results indicate that accurate information on parameter values influenced how the subjects perceived the indoor air quality (IAQ) but not how they perceived the thermal, acoustic, or visual environmental quality. The subjects rated the IAQ more positively when they were informed that there were nonzero ventilation rates. The qualitative ratings influenced the subjects' perceptions of all four environmental factors, but in different directions. The subjects generally had more positive sensation and higher satisfaction when they were told that the parameter values and qualitative ratings were more favorable than the test conditions. However, the improved sensation and satisfaction were often not as good as when the environmental conditions were actually improved and the subjects were provided with accurate

information. These findings affirm the critical need for more research on the impacts of information on perceptions of the indoor environment.

Keywords: Building sensors, thermal, acoustic, visual, indoor air quality

Conflict of Interest

The authors have no conflicts of interest to declare.

Acknowledgments

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1 Introduction

Indoor environmental quality (IEQ) has been found to impact health, comfort and productivity [1–4]. IEQ is commonly considered in terms of four elements: thermal, acoustic, lighting and air quality [5], and each element can be described by measurable parameters, such as temperature, relative humidity, sound pressure, illuminance, and air contaminant concentrations. In the past, environmental measurements were limited by the costs of both the equipment and the personnel required to collect, process, and analyze data [6]. Developments in sensor and wireless technology have greatly reduced the cost and technical expertise required for environmental monitoring [7], and various monitoring and visualization systems have been implemented in buildings [6,8–16]. The collected data can be stored on-site or transferred to a cloud platform that enables access through any connected device, including smart phones. Some systems incorporate software to automatically apply analysis algorithms and provide qualitative ratings of IEQ and improvement suggestions. An increasing number of portable, easy-to-use, and low-cost environmental monitoring products are also available and accessible to individuals [17].

The broad application of indoor monitoring systems and devices enables the identification of IEQ problems and has the potential to guide building operations and improve satisfaction and productivity [18]. Monitoring also provides the opportunity to provide occupants with quantitative information about the environment, with potential impacts on their perceptions of existing conditions and longer-term learning about the relevant parameters.

Human perception is considered to be both physiological and psychological [19]. Many studies have exposed subjects to various indoor environmental conditions and asked about some or all of their perceptions of thermal, acoustic, visual and indoor air quality (IAQ) [20]. Thirty studies (listed in Table A.1) that simultaneously measured the physical indoor environment and subject/occupant perceptions were reviewed, including studies conducted under both laboratory and field conditions. Twelve of the studies examined perceptions of multiple aspects of thermal, acoustic, visual and IAQ, and the others surveyed perceptions of only one aspect. While 19 of the 30 studies did not clarify whether the subjects were informed about the exposed environmental conditions, ten specified that the subjects were not informed, and one specified that the subjects were informed. Blinding subjects to test conditions is intended to avoid psychological effects and evaluate occupants' perceptions under the common condition of such information being unavailable. For example, Wargocki et al. exposed 30 subjects to two IAQ conditions with different pollution loads and surveyed their perceived IAQ, and the subjects were intentionally blinded to the presence of the pollution source and measurement throughout the tests [21]. However, the reviewed studies provided no quantitative or qualitative analysis of the potential psychological effects of such information.

Only one of the identified studies, conducted by Rohles and Kerulis in 1980, addressed the hypothesis that information on environmental conditions can influence occupants' perception of the environment [22]. In this experiment, subjects who were informed of temperature values were found to perceive the indoor thermal environment to be warmer than subjects who were not informed.

An important complexity related to the question of how information about environmental conditions may affect perceptions is many subjects' potentially limited familiarity with metrics for features other than temperature and humidity. Many systems designed to inform people of environmental conditions commonly use qualitative ratings for parameters. For consumer-grade devices, ratings are typically presented in different colors, e.g., green for good, yellow for acceptable, and red for poor. This model is also used in commercial building monitoring systems, such as the sentient ambient monitoring of buildings in Australia (SAMBA) developed by Parkinson et al. [8] (see Figure 1). The overall "good" rating is presented prominently in green, and numerical values are highlighted (in red) only when they are outside the designated acceptable range (e.g., CO_2 above 1000 ppm, as shown).

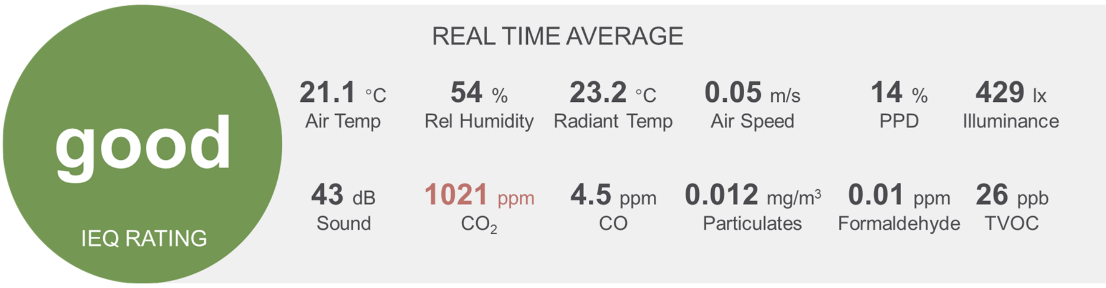

Figure 1 The SAMBA dashboard, which rates indoor environmental quality as good based on the measurement results, used with permission from Building and Environment [8]

Another unresolved question is whether inaccurate environmental information or a rating based on inaccurate information can impact perception. Inaccurate information may result from low-quality or faulty sensors or from limited or inappropriate measurement locations.

The study reported herein was designed as an exploratory investigation of the impact of various types of information on occupants' perceptions of and satisfaction with indoor environmental conditions. The following questions were addressed:

1. How does quantitative information impact perceptions of indoor environmental conditions?

2. Do qualitative ratings for environmental parameters impact perceptions differently than quantitative information?

3. Do ratings and values that are more favorable than the actual conditions yield more favorable perceptions?

2 Methodology

In this experimental study, human subjects were exposed to varied indoor environmental conditions, provided with different types of information, and then asked about their sensation and satisfaction with the environment. Discrete variations in temperature, sound pressure, illuminance, and ventilation rate were established in a research room with office furnishings. Three groups of 16 subjects were exposed to the same sets of physical conditions on different days, and each group was provided with two different types of information from among the following:

1. No information. (Groups 1 and 2)

2. Quantitative information about selected parameters. (Group 1)
3. Qualitative ratings (Good, Fair or Poor) with visual cues (green, yellow, or red signage). (Group 2)
4. Quantitative parameter values and qualitative ratings. (Group 3)
5. Parameter values and ratings that represented the conditions as being one level more favorable than they actually were. (Group 3)

The subjects' sensation and satisfaction with each environmental factor were measured using a questionnaire. The experiment was approved by the Ethics Review Committee for Life Sciences Study of Central China Normal University under registration number CCNU-IRB-2018-012. Written informed consent was obtained from the subjects prior to their participation in the experiment.

2.1 Subjects

The research subjects were 48 students from Chongqing University who responded to an online recruitment advertisement posted on social media and on a campus forum. Interested students responded via an online survey website. The advertisements, survey, and all study communications were in Chinese. Subjects were selected from the applicant pool based on their availability and the requirement that they be in good general physical and mental health and nonsmokers. Students within the research group conducting the experiment or with any prior knowledge of the experimental objectives were excluded. In compliance with university rules during the pandemic, applications from off-campus personnel were not accepted.

Presumably due to the burden of traveling between campuses, which was exacerbated during the pandemic (see Appendix A for more information), 102 of the 112 students who applied were from the local campus, which is occupied by the Civil Engineering, Environmental Science, Biology and Architecture departments. Fourteen of the 48 selected subjects studied the built environment (BE), and 15 studied heating, ventilation and air conditioning (HVAC). The remaining 19 subjects were students in Structural Engineering, Water Supply & Drainage, and Materials Science and Biology. To investigate the potential effect of educational background or prior knowledge on their understanding of the parameters used in the study, the subjects were asked to complete a questionnaire before the first test to assess their familiarity with each parameter; the response options were “Not familiar at all”, “Not very familiar”, “Somewhat familiar”, and “Very familiar”. The responses were assigned numerical values of 1–4, respectively, for analysis. The impact of the subjects’ technical background is discussed in subsection 3.7.

The subjects had a mean age of 23 years (standard deviation [SD]=1.2) and a mean body mass index (BMI) of 21.2 (SD=1.9; range of 18.5–24.0).

The subjects were divided into three groups, with eight males and eight females in each. The subjects with a background in BE or HVAC were evenly assigned to the three groups, with nine in Group 1 and eight each in Groups 2 and 3. The statistical power was calculated based on the acquired sample size [23]. The actual mean effect size (Cohen’s d) of significant effects identified by paired t-test in this study was 0.92. With this effect size, a significance level of 0.05 and 16 subjects in each group, the statistical power of the paired t-test was 0.93, which is higher than the generally required level of 0.8 [23,24]. The power calculation was performed in R with the package ‘pwr’ [25].

At recruitment and in the consent form, the subjects were informed that they would be asked to work under varied indoor environmental conditions and report their sensation and satisfaction with the conditions. The subjects were not explicitly informed that environmental information would be part of the study until their group was provided with information in an experiment. For Groups 1 and 2, there was no mention of such information until the second round of experiments. Group 3 was provided with the information in the first round. When the information was first provided for a group, it was introduced by an experimenter so that all subjects could note it. The subjects were not informed that assessing the potential effect of the information was an objective of the study.

2.2 Experimental facilities

The tests were carried out in an IEQ lab at Chongqing University, as shown in Figure 2 (a). The dimensions of the room are 7.9 m by 7.9 m by 2.9 m. The room has two north-facing windows, which remained closed during the tests. Shutters were used to block natural light throughout the tests to maintain a stable level of indoor illuminance. The distance between the windows and test area was approximately 1.2 m. A video display (155 cm by 87 cm) was placed in the front of the room to present environmental information. The locations of the environmental monitoring instruments are illustrated in Figure 2 (b). The measured parameters and equipment used to collect data are shown in Table 1. The illuminance level of each table was measured only before each test; other parameters were monitored continuously during the tests. The U-values of the fabric components of the test room are presented in Table A.2.

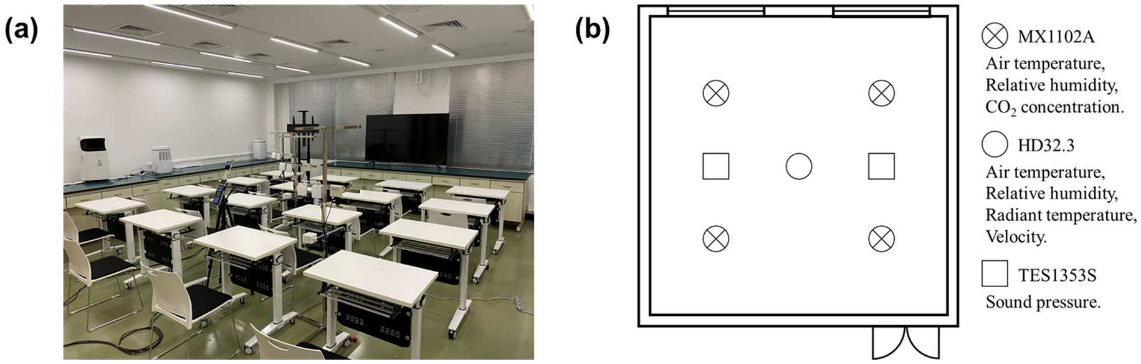

Figure 2 (a) Layout of the IEQ lab, (b) Location of environmental monitoring instruments; illuminance at each table was measured only before tests.

Table 1 Measured parameters and technical data of instruments

Instrument	Measured parameter	Range	Accuracy [a]
MX1102A by ONSET HOBO	CO_2	0–5000 ppm	±50 ppm
	Air temperature	0–50 °C	±0.21 °C
	Humidity	1–90%	±2%
HD32.3 by Delta OHM	Air temperature	-40–100 °C	±0.1 °C
	Radiant temperature	-10–100 °C	±0.1 °C
	Humidity	1–90%	±1.5%
	Velocity	0.1–5 m/s	±0.2 m/s (0–1 m/s) ±0.3 m/s (1–5 m/s)
Model 1399 by TES	Illuminance	0.01–999900 lx	±3% of measurement
Model 1353S by TES	Sound pressure	30–130 dB	±1 dB

a: As specified in the product literature.

Four fan coils were used to control the thermal environment in the room, and one fan coil was used to cool ventilation air. All fan coils were operated at their lowest setting (380 m^3/h, rated cooling capacity of 2782 W), which provided air speeds at head heights below 0.05 m/s to avoid feelings of draft. Three instruments (MX1102A by ONSET HOBO) recorded the temperature, and one recorded the predicted mean vote (PMV) (HD32.3 by Delta OHM).

The sound pressure in the room with the air conditioning system operating at the lowest setting was 38 dBA. The sound level in the room was increased with prerecorded fan noise provided via six speakers installed on the ceiling. Integrated sound level meters (Model 1353S by TES Electrical Electronic Corp.) were used to ensure that the sound pressure was controlled at the designated level and to record values during the tests.

Illuminance levels were set with 48 light-emitting diodes (LEDs) controlled by a computer. Each LED had a rated power of 24 W and a luminous flux of 3120 lumens. The color temperature of the LEDs was 4000 K, as recommended for offices by the Chinese standard [26].

Two fans with adjustable flow from 120–1200 m^3/h each were used for ventilation. Velocity probes installed in the ducts were used to estimate the ventilation rate. Notably, when the ventilation system was turned off to simulate a ventilation rate of 0 m^3/h per person, 49 m^3/h of fresh air infiltrated into the room. Infiltration was measured using pure CO_2 as a tracer gas and calculated in accordance with the Chinese standard for physical parameter examination methods [27].

2.3 Controlled indoor environment

Indoor environmental conditions were set at prescribed combinations of temperature, illuminance, sound pressure and ventilation rate. Each parameter was presented at three levels corresponding to three ratings – Good, Fair and Poor – as shown in Table 2.

Table 2 Presented levels for each parameter and the corresponding ratings

Parameter	Level	Rating
Temperature	25 °C	Good
	27 °C	Fair
	29 °C	Poor
Illuminance	500 lx	Good

	300 lx	Fair
	150 lx	Poor
Sound pressure	40 dBA	Good
	45 dBA	Fair
	50 dBA	Poor
Ventilation rate per person	60 m^3/h	Good
	30 m^3/h	Fair
	0 m^3/h	Poor

The qualitative rating for each temperature level was assigned based on the predicted mean vote-predicted percentage dissatisfied (PMV-PPD) model established by Fanger et al. [28]. In that model, PMV values at 25, 27 and 29 °C are approximately -0.1, 0.7 and 1.4, respectively, when radiant temperature is equal to air temperature, relative humidity is 65%, clothing insulation is 0.57 clo for trousers and short-sleeved shirt according to ASHRAE standard 55 [29], velocity is below 0.05 m/s, and metabolic rate is 1. A PMV value between -0.5 and 0.5 is recognized as comfortable by most thermal environmental standards [29–31]; thus, 25 °C is considered Good. A PMV value of 0.7 at 27 °C is slightly beyond the limit of the comfort zone, which makes it Fair. A PMV value of 1.4 at 29 °C is far from the comfort zone, which makes it Poor.

According to the Chinese lighting design standard [26], the minimum illuminance values for general offices and premium offices are 300 and 500 lx, respectively. Thus, 300 and 500 lx were considered Fair and Good. An illuminance of 150 lx is insufficient for an office environment and is thus rated as Poor. Natural light was completely blocked throughout the tests.

According to the Chinese sound insulation design standard [32], the general and high-performance requirements of indoor sound pressure in shared offices are 45 and 40 dBA, respectively. Thus, the ratings of 40, 45 and 50 dBA are Good, Fair, and Poor, respectively.

A ventilation rate of 30 m^3/h for each person is required as a minimum by the Chinese heating, ventilation, and air conditioning (HVAC) system design standard [33]. Mechanical ventilation rates of 0, 30 and 60 m^3/h per person were provided, corresponding to ratings of Poor, Fair and Good, respectively.

2.4 Experimental procedure

Each group experienced two rounds of the same four series of controlled indoor environmental conditions and was provided with different types of environmental information, as shown in Figure 3 and Table 3. The subjects in each group were asked not to discuss the tests with anyone in a different group. In the first round, both Group 1 and Group 2 subjects experienced all of the indoor environmental conditions without any information. In the second round, Group 1 was informed of the environmental parameter values and Group 2 was provided with the ratings shown in Table 2. In the first round, Group 3 was provided with both parameter values and ratings; in the second round, this group was provided with parameter values and ratings which were upgraded one level compared to the actual conditions. For example, when the air temperature was 27 °C, corresponding to a Fair rating in this study, Group 3 was told that the air temperature was 25 °C and the thermal environment was Good. Group 3 was presented with only the (actual) Poor and Fair conditions in the second round. Throughout the experiment, the subjects were not told that the information provided could be inaccurate.

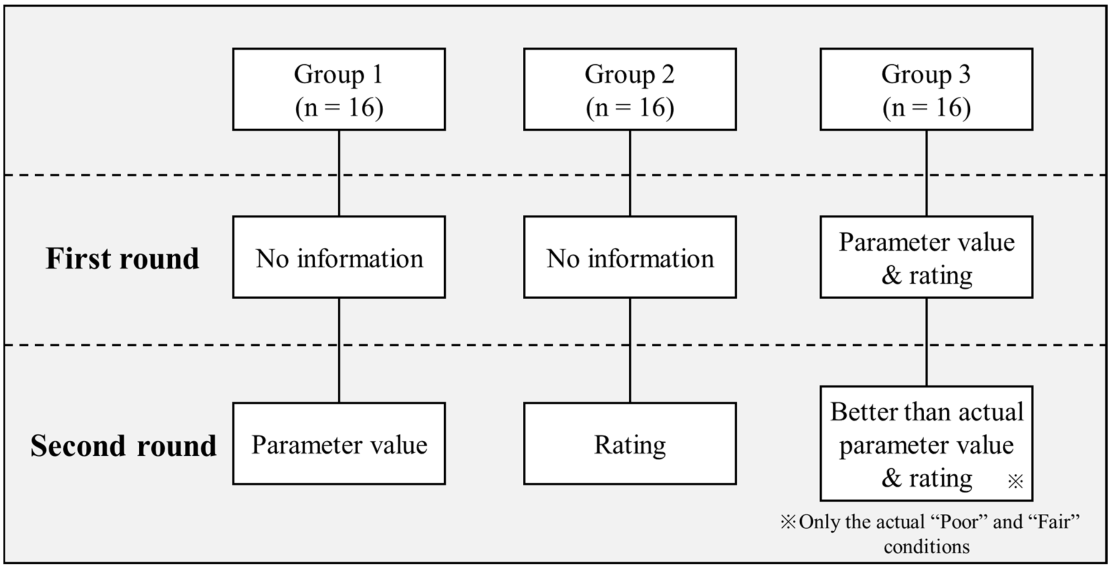

Figure 3 Experimental flow diagram

The test schedule is shown in Table 3. The tests were carried out each day from 1:45 pm to 5:15 pm to avoid the effect of time of day on the subjects' perceptions. During each 210-minute test period, the subjects were exposed to three controlled environmental conditions; each lasted for 60 minutes, and there was a 15-minute interval after each condition. For Group 3, only two tests were carried out in the second round from 1:45 pm to 4:00 pm. The subjects were asked to arrive 15 minutes before the tests. To avoid interactions among environmental factors, only one parameter was changed each day [34,35]. The changing parameter was presented in the order of Good then Fair then Poor, while the other controlled parameters remained Good. The conditions were not presented in randomly varying order to support the within-group control design and the need to keep the sequence consistent in the two rounds of exposure. In addition, the contrast effect from continuous exposure was minimized by narrowing the gap in parameters between adjacent conditions. The potential uncertainty involved in the approach is discussed in the Limitations subsection. The mean high and low ambient temperatures during the test days were 35 °C and 26 °C, respectively. The mean ambient temperature in the hour before the experiments was 33 °C.

During each hour-long test, the subjects were asked to stay seated and to move only as necessary, e.g., to use the restroom. The subjects performed normal office work, such as typing, writing, and reading, during the test. Most of the subjects worked with their laptops or pads during the tests. They were not permitted to use headphones and were asked not to talk, listen to music, or watch videos to avoid the influence of such stimuli on acoustic perceptions. They were asked to wear short-sleeve shirts, long trousers and sneakers, with the aim of having clothing insulation of approximately 0.57 clo [29]. During the intervals between tests, the subjects were relocated to an adjacent office, and the experimental room was adjusted to the next condition. The ventilation system of the test room was operated to provide 2400 m^3/h (air change rate of 13 h^{-1}) during this interval, and the CO_2 concentration was lowered to below 500 ppm. The adjacent office occupied by the students during the intervals between tests was set to 27 °C air temperature, 300 lx illuminance, 45 dBA sound pressure and 30 m^3/s per person ventilation rate. The subjects were allowed to move and talk but not to perform intense physical activities during the interval.

Table 3 Test schedules

Date	Group	Changed parameter and levels		Environmental information
2020/7/25	1	Sound pressure (dBA)	40→45→50	None
2020/7/26	2	Sound pressure (dBA)	40→45→50	None
2020/7/27	3	Sound pressure (dBA)	40→45→50	Value and rating
2020/7/28	1	Temperature (°C)	25→27→29	None
2020/7/29	2	Temperature (°C)	25→27→29	None
2020/7/30	3	VR per person (m^3/h)	60→30→0	Value and rating
2020/7/31	1	VR per person (m^3/h)	60→30→0	None
2020/8/1	2	VR per person (m^3/h)	60→30→0	None
2020/8/2	3	Temperature (°C)	25→27→29	Value and rating
2020/8/3	1	Illuminance (lx)	500→300→150	None
2020/8/4	2	Illuminance (lx)	500→300→150	None
2020/8/5	3	Illuminance (lx)	500→300→150	Value and rating
2020/8/6	1	Temperature (°C)	25→27→29	Parameter value
2020/8/7	2	Temperature (°C)	25→27→29	Rating level
2020/8/8	3	Sound pressure (dBA)	45→50	Upgraded value and rating
2020/8/9	1	Sound pressure (dBA)	40→45→50	Parameter value
2020/8/10	2	Sound pressure (dBA)	40→45→50	Rating level
2020/8/11	3	Temperature (°C)	27→29	Upgraded value and rating
2020/8/12	1	VR per person (m^3/h)	60→30→0	Parameter value
2020/8/13	2	VR per person (m^3/h)	60→30→0	Rating level
2020/8/14	3	VR per person (m^3/h)	30→0	Upgraded value and rating
2020/8/15	1	Illuminance (lx)	500→300→150	Parameter value
2020/8/16	2	Illuminance (lx)	500→300→150	Rating level
2020/8/17	3	Illuminance (lx)	300→150	Upgraded value and rating

2.5 Environmental information

Information about the provided conditions was presented both on the display placed in the room and on the paper copy of the questionnaire (introduced in subsection 2.6). Information on the display was presented at a recognizable size throughout the test. The ratings were presented using the Chinese characters for Good, Fair or Poor in green (RGB: 0, 210, 110), yellow (RGB: 222, 169, 0) or red (RGB: 192, 0, 0), respectively. Examples are shown in English in Figure 4 and in Chinese, as presented to the subjects, in Figure A.1 (see Appendix A). The display was turned off during the first round, in which no information was provided, for Groups 1 and 2. Environmental information was also provided in the questionnaire next to the relevant questions, as shown in Figure A.2.

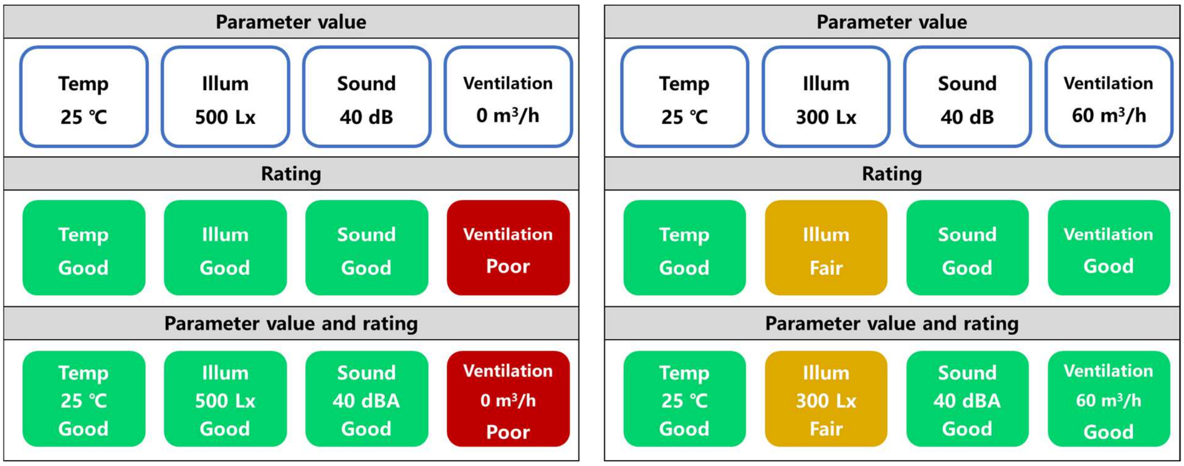

Figure 4 Examples of environmental information presented on the screen. The information was presented in Chinese in the tests, as shown in Figure A.1.

2.6 Subject reporting of sensation and satisfaction

At the end of each one-hour exposure event, the subjects were asked to report their sensations and satisfaction with the four indoor environmental factors (thermal, acoustic, visual and IAQ) on a paper copy of the questionnaire before they left the room. Previous studies have found that, in contrast to the symmetrical relationship between thermal sensation and satisfaction, the correlations between the other three sensations and corresponding satisfaction levels are more likely to be monotonic [28,34,36]. For example, a sensation of bright/quiet/fresh was often associated with higher satisfaction than one of dim/noisy/stuffy, while cold and hot were always considered less satisfying as compared to neutral. Therefore, two scales were used to measure the subjects' sensations and satisfaction with different environmental aspects. A symmetrical 7-point thermal sensation vote (TSV) ranging from -3 (cold) to 3 (hot) was used to rate thermal sensation. An increasing 11-point scale from 0 (Very noisy/dim/stuffy/dissatisfied) to 10 (Very quiet/bight/fresh/satisfied) was used to measure sensations and satisfaction for other environmental parameters; the guides are shown in Table A.3 (see Appendix A).

2.7 Statistical analysis

Paired t-tests were used to assess whether the average scores were significantly different when the subjects within a group were provided with different information in the two rounds of exposure; the Benjamini–Hochberg (BH) method was used to adjust the resulting P values to reduce the probability of type I errors [37]. The level of significance based on adjusted P values is indicated as follows: ns ($P > 0.05$), * ($0.01 < P \leq 0.05$), ** ($0.001 < P \leq 0.01$), and *** ($P \leq 0.001$).

3 Results

Figures 5 to 12 present the subjects' average sensation and satisfaction with the thermal, acoustic, visual, and IAQ conditions at each level when they were provided with various types of information. The error bars represent the standard error. Within each panel, the conditions are presented in the order in which the subjects experienced them.

3.1 Perceived thermal environment

As expected, all groups rated the thermal environment as hotter and reported lower satisfaction at higher temperatures. The thermal sensation and satisfaction of the subjects in Group 1 did not change significantly after they were informed of the temperature, as shown in Figures 5 and 6. For Group 2, the thermal sensation at 27 °C was significantly closer to neutral when the subjects were informed that the temperature was Fair than when they received no information about it, and their thermal satisfaction was higher. However, thermal sensation and satisfaction for the subjects in this group did not change at 25 °C or 29 °C when they were provided with ratings. An improvement in thermal sensation and satisfaction was reported by the subjects in Group 3 at 27 °C when they were told that the temperature was 25 °C with a Good rating. Thermal sensation and satisfaction under this condition were not significantly different than the values when the temperature was actually 25 °C and accurate information was provided. Moreover, when the subjects in Group 3 was exposed to a temperature of 29 °C and (misleadingly) informed that the temperature was 27 °C and Fair, they reported the condition as significantly warmer with lower satisfaction than in the test in which they actually experienced a 27 °C temperature (P < 0.001).

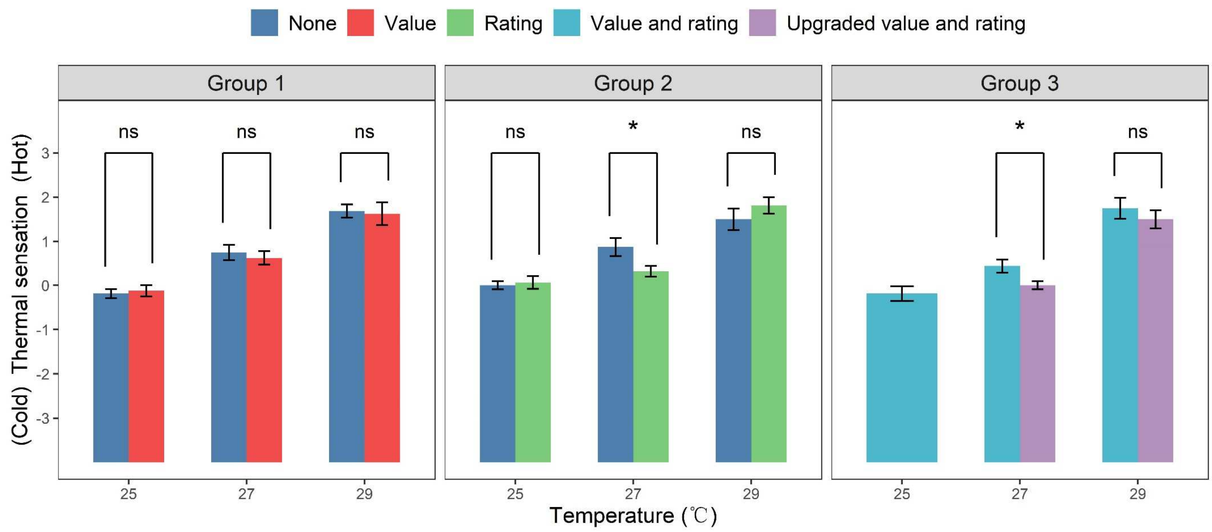

Figure 5 Thermal sensation at each controlled temperature and type of information provided

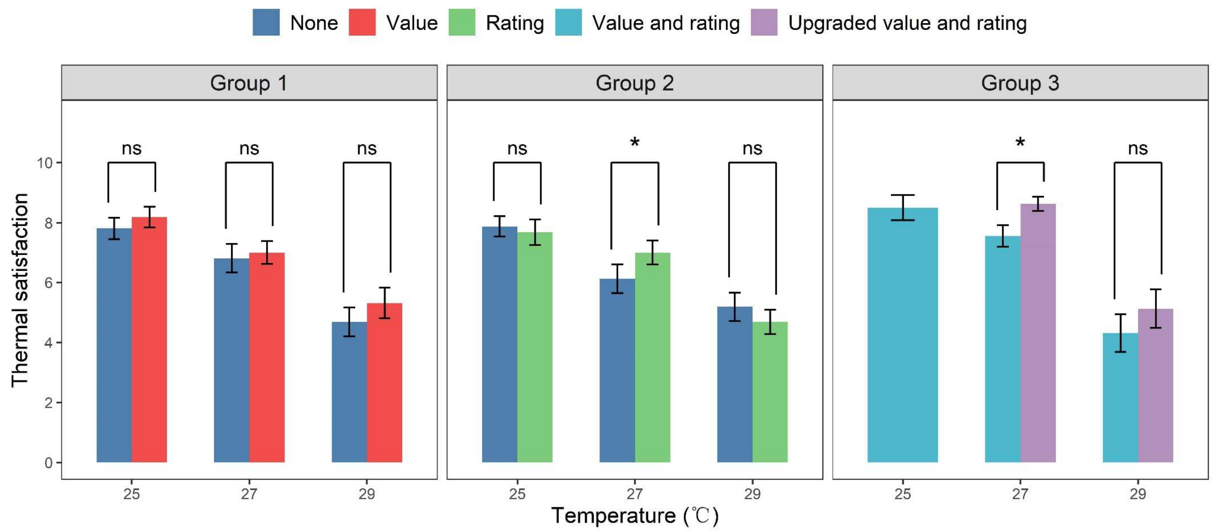

Figure 6 Thermal satisfaction at each controlled temperature and type of information provided

3.2 Perceived acoustic environment

Acoustic sensation and satisfaction did not change significantly when the subjects in Group 1 were informed of the sound pressure (Figure 7 and Figure 8). When the subjects in Group 2 was provided with ratings, their sensation was closer to noisy when they experienced Fair (45 dBA) and Poor (50 dBA) acoustic conditions, and their satisfaction with the acoustic environment was lower. There were decreases in sensation of 1.7 and 1.9 units at 45 dBA and 50 dBA, respectively, as well as decreases in satisfaction of 1.3 and 1.4. The subjects in Group 3 perceived a better acoustic environment when they were provided with better-than-actual values and ratings than when they received accurate information. Under the 45 dBA and 50 dBA conditions, sensation increased by 1.4 and 1.2 and acoustic satisfaction increased by 1.4 and 1.1, respectively. However, the sensation and satisfaction scores were still lower than when the subjects actually experienced the better acoustic conditions and were provided with correct information.

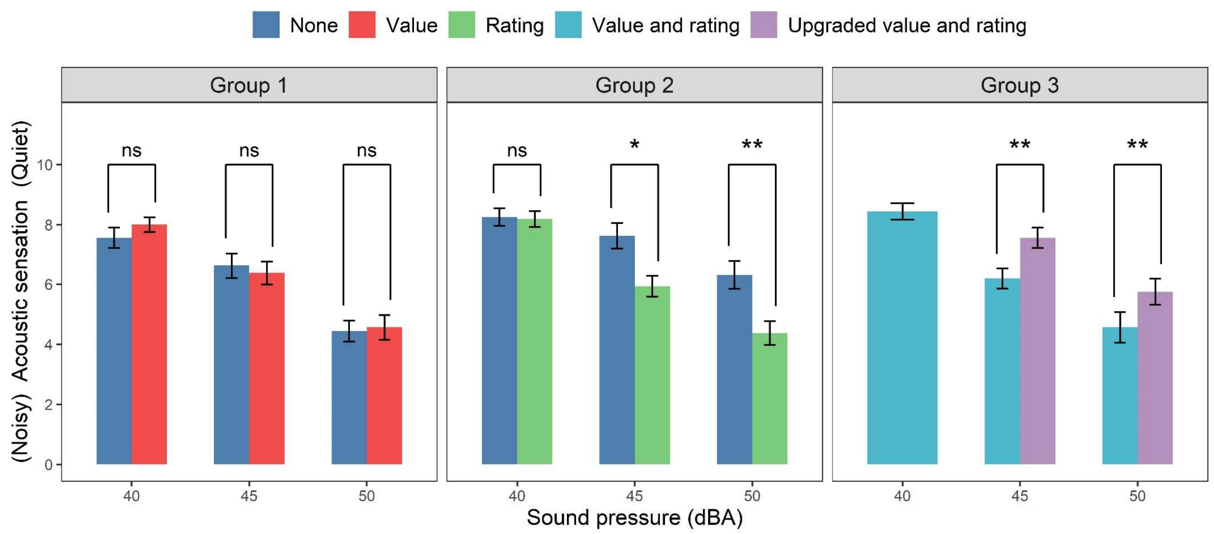

Figure 7 Acoustic sensation at each controlled sound pressure and type of information provided

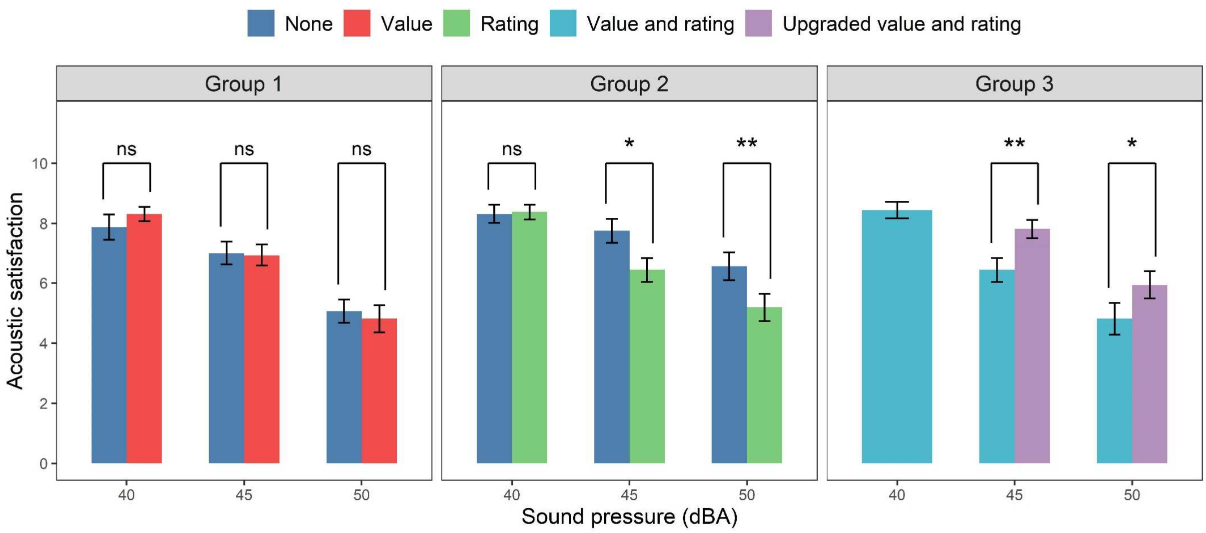

Figure 8 Acoustic satisfaction at each controlled sound pressure and type of information provided

3.3 Perceived visual environment

The visual sensation reported by the subjects in Group 1 was closer to "bright" when they were informed that the controlled illuminance was at 500 lx (Figure 9). Their visual satisfaction increased slightly as well (Figure 10), but the change was not statistically significant. Visual sensation and satisfaction were not affected by informing the subjects that the illuminance was 150 lx or 300 lx. When the subjects in Group 2 were provided with illuminance ratings, their sensation of light significantly increased (by 0.7) at the 500 lx condition, and their visual satisfaction significantly decreased (by 0.9) at the 150 lx condition compared to when they received no information. However, their sensation at the 150 lx condition and their satisfaction at the 500 lx condition did not change significantly. The subjects in Group 3 reported a significantly brighter and more satisfactory visual environment when they were presented with the better-than-actual illuminance value and rating than when they were informed correctly of the illuminance conditions. Their sensation and satisfaction increased by 1.2 and 1.4, respectively, at the 150 lx condition and by 2.1 and 1.6, respectively, at the 300 lx condition. The improved sensation and satisfaction were not greater and sometimes less than those when the subjects in

Group 3 were actually exposed to a higher illuminance level and informed of the correct illuminance and rating.

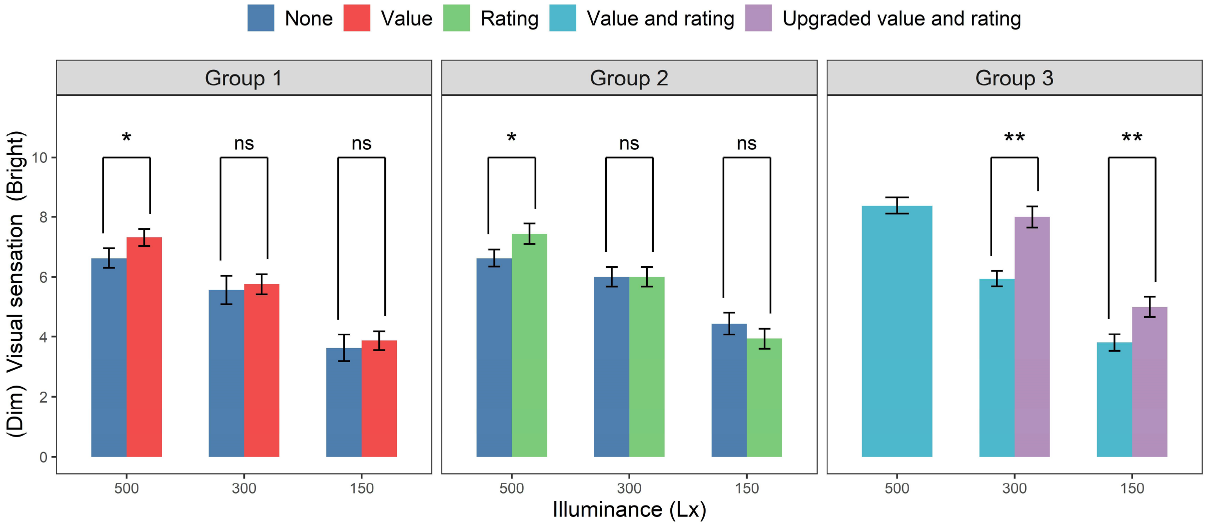

Figure 9 Visual sensation at each controlled illuminance and type of information provided

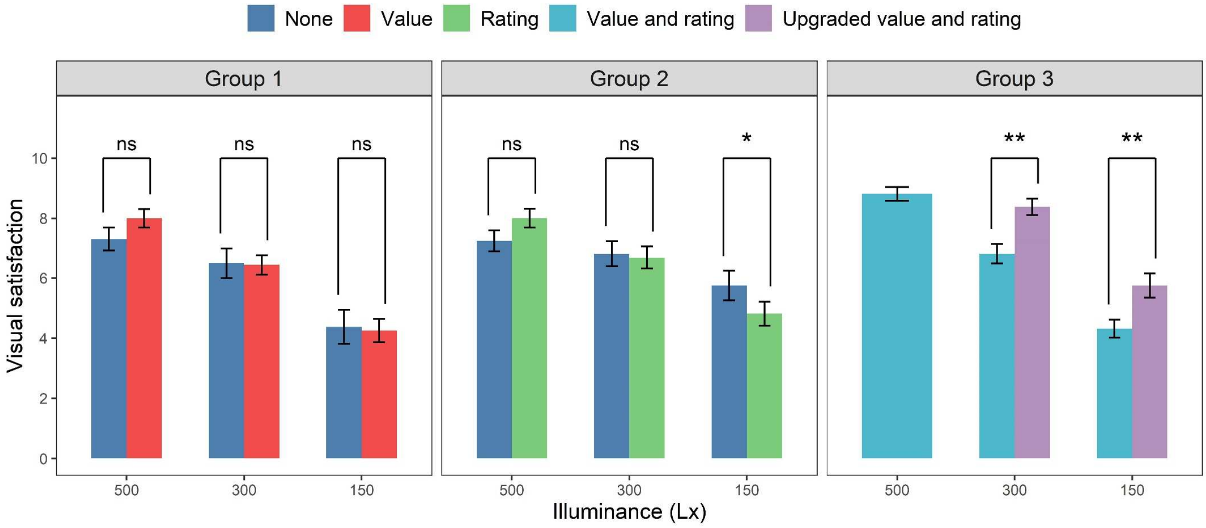

Figure 10 Visual satisfaction at each controlled illuminance and type of information provided

3.4 Perceived IAQ

When provided with the actual ventilation rates, the subjects in Group 1 perceived the air as significantly more “fresh” (Figure 11) and had higher satisfaction (Figure 12) at 30 m^3/h/person (P<0.01) and 60 m^3/h/person (P<0.05). The parameter information did not change the perception of IAQ under the condition of no ventilation. Compared to their experience with no information provided, the subjects in Group 2 reported the air as being significantly better with higher satisfaction at 60 m^3/h/person and significantly worse with lower satisfaction at 0 m^3/h/person when provided with the ratings of Good and Poor, respectively. The Fair rating caused no change in sensation or satisfaction at 30 m^3/h/person. For Group 3, misinforming the subjects of the upgraded ventilation rate and rating significantly improved their sensation and satisfaction with IAQ at actual ventilation rates of 0 m^3/h/person and 30 m^3/h/person. The improved satisfaction with IAQ was approximately equal to that when the subjects experienced a higher ventilation rate and were provided with correct information.

The perceived IAQ of subjects in Groups 1 and 2 did not significantly change with ventilation rate when they were not informed of values and ratings, a result that is inconsistent with many prior studies that have reported that perceived IAQ was associated with ventilation rate when subjects were blinded [38]. The shorter exposure period in this study is a possible explanation for the different results. Some studies have reported that subjects did not perceive different IAQ levels during exposure (but only at the beginning or reentering) to different ventilation rates that lasted approximately 4 hours [39–41], while a significant difference in perceived IAQ was observed over a longer exposure, such as 8 hours [42].

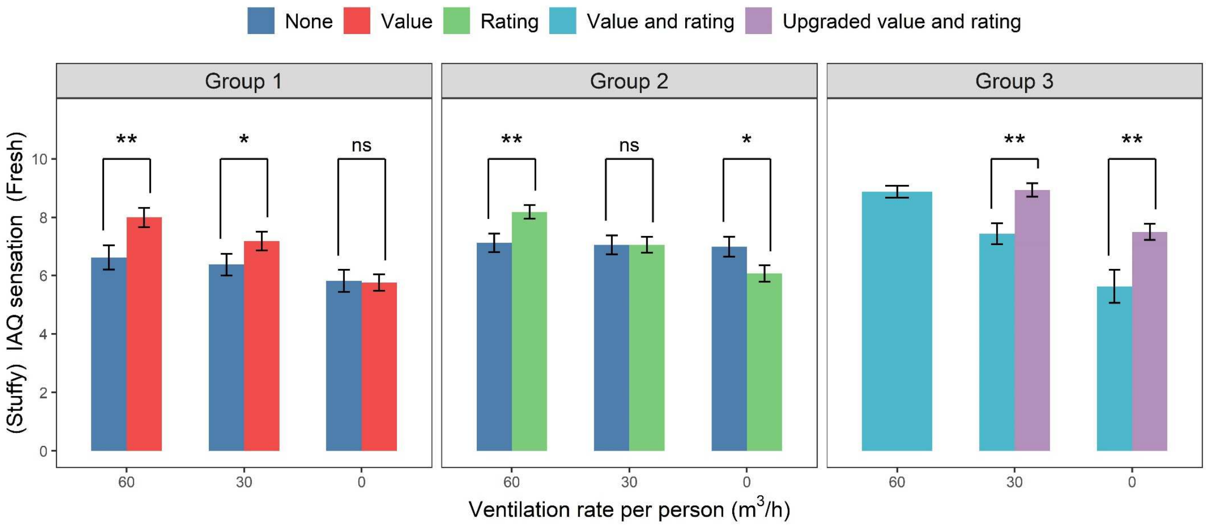

Figure 11 IAQ sensation at each controlled ventilation rate and type of information provided

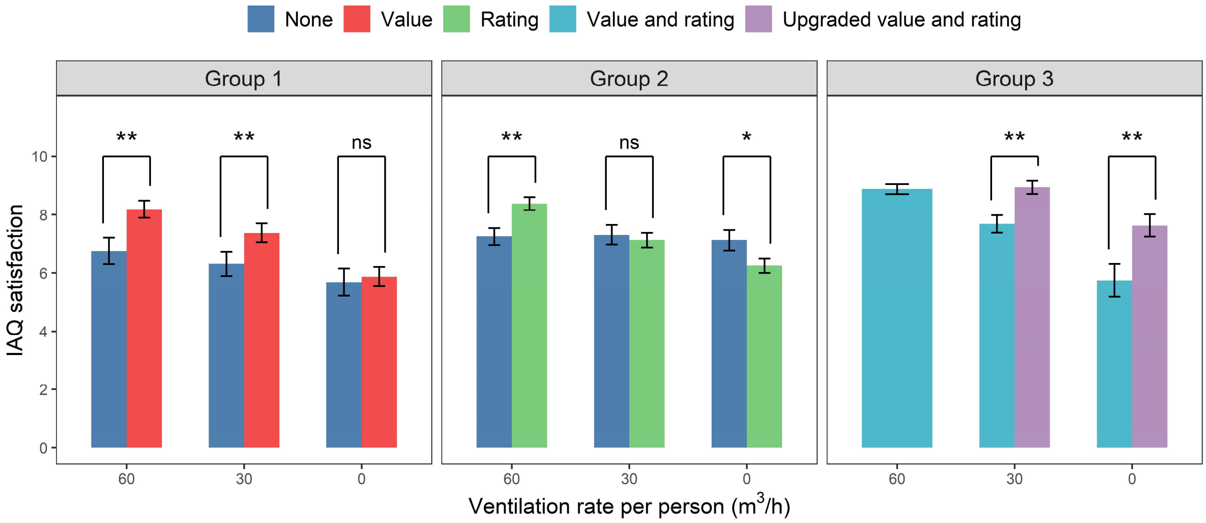

Figure 12 IAQ satisfaction at each controlled ventilation rate and type of information provided

3.5 Gender difference

Satisfaction with the four environmental factors throughout the experiment was compared between female and male subjects, as shown in Figure 13. The error bars represent standard error. The Welch two-sample t-test was used to identify any significant difference. The male subjects were found to be less forgiving than the female subjects in warmer environments at 27 °C and 29 °C. The mean differences in scores were 0.6 at 27 °C and 0.4 at 29 °C. However, due to the significant standard error within each gender group, this difference was not statistically significant (P>0.05). No significant difference between the male and female subjects was found in satisfaction with the acoustic and visual environments. The male subjects rated IAQ more positively under unventilated conditions, while they were less satisfied than the female subjects at a ventilation rate of 30 m^3/h per person. However, the difference in IAQ satisfaction did not reach significance (P>0.05). Overall, no statistically significant difference was found between the two gender groups.

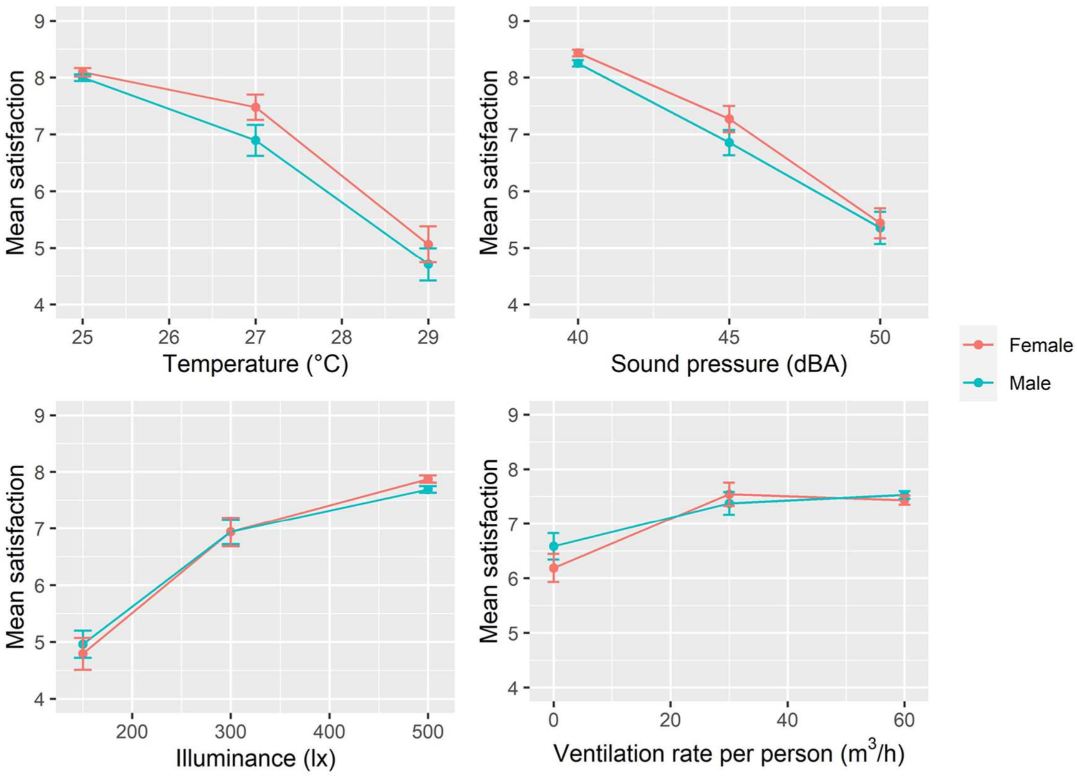

Figure 13 Gender difference in satisfaction with different environmental factors

3.6 Individual difference

Paired t-tests were used to identify whether the subjects' sensation of and satisfaction with environmental factors changed significantly with all types of provided environmental information. A significant impact was defined as one in which most subjects in a group changed their perceived sensation or satisfaction in the same direction; therefore, even for such impacts, some subjects were not influenced. The probability density of the mean absolute satisfaction difference for each subject was calculated when exposed to different conditions of environmental information, as shown in Figure 14. This analysis was performed only for controlled conditions in which a significant impact of environmental information was found (shown in Table 4). The mean absolute difference was 1.37, and the median was 1.0. After receiving different environmental information, 57% of the subjects changed their satisfaction by 1–2 points on an 11-point scale. The overall percentage of subjects whose satisfaction did not change was 15%. The highest percentage of unchanged satisfaction was 31% for thermal satisfaction, well above other environmental factors, indicating that thermal satisfaction was least susceptible to environmental information. Satisfaction changed by three or more points for 13% of the sample, indicating that some subjects were very sensitive to environmental information.

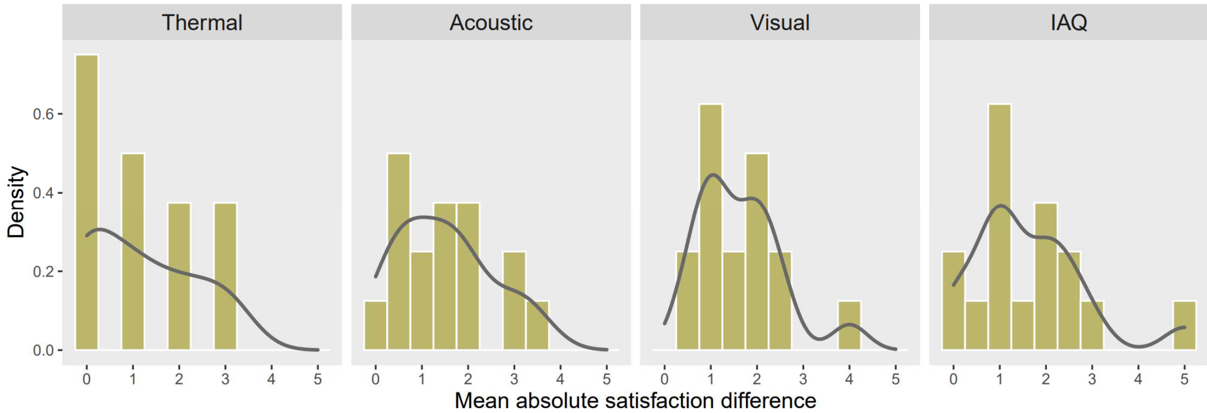

Figure 14 Probability density of mean absolute satisfaction difference for each subject resulting from changes in all types of environmental information, including only conditions with significant changes identified by paired t-test

3.7 Effect of subject technical background

To assess the potential bias of subjects with an educational background in BE and HVAC possibly having different perceptions of the conditions or different reactions to the parameter information, the subjects' self-reported familiarity with IEQ parameters by educational background was analyzed. The mean score of familiarity for each parameter was calculated based on a 4-point scale, with a higher score indicating greater familiarity. The results are presented in Figure 15.

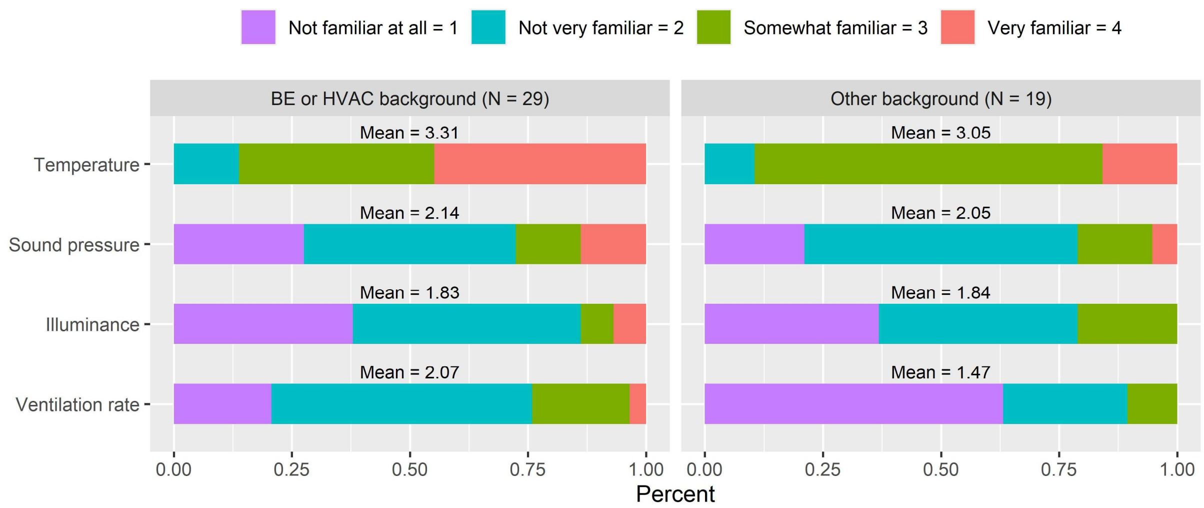

Figure 15 Subjects' self-reported familiarity with environmental parameters, divided into groups with and without BE and HVAC background. The mean score of familiarity for each parameter is presented.

Temperature was the parameter that was most familiar to both groups, with no subjects reporting that they were not familiar with it at all. The subjects with a BE or HVAC background had a higher familiarity score for temperature, although this difference was very slight and did not reach significance at the level of $p \leq 0.05$. The familiarity scores of illuminance and sound pressure were very similar between the two groups, and both were lower than the scores for temperature. In contrast, a significant difference in familiarity with ventilation rate between the two groups was identified by t-test ($P < 0.01$), and the difference of 0.6 points was notable.

The mean sensation and satisfaction between the BE and HVAC group and the other group were also compared, as shown in Table A.4. This analysis found no significant differences in sensation and satisfaction with the thermal, acoustic and visual environments based on the subjects' educational background. The subjects without a BE or HVAC background were more positive when rating the IAQ than the subjects with a BE or HVAC background ($P<0.001$), with small differences of 0.36 for sensation and 0.2 for satisfaction on the 10-point scales.

4 Discussion

A summary of the impacts of environmental information on subjects' sensation and satisfaction with the controlled environmental factors is presented in Table 4.

Table 4 Impact of the environmental information provided on the subjects' sensation and satisfaction with the controlled environmental factors [a]

Environmental parameters	Levels	Ratings	Parameter value vs. no information		Rating vs. no information		Upgraded value and rating vs. accurate value and rating	
			Satisfaction	Sensation	Satisfaction	Sensation	Satisfaction	Sensation
Temperature	25 °C	Good	--	--	--	--	na	na
	27 °C	Fair	--	--	Higher	Cooler	Higher	Cooler
	29 °C	Poor	--	--	--	--	--	--
Sound pressure	40 dBA	Good	--	--	--	--	na	na
	45 dBA	Fair	--	--	Lower	Noisier	Higher	Quieter
	50 dBA	Poor	--	--	Lower	Noisier	Higher	Quieter
Illuminance	500 lx	Good	--	Brighter	--	Brighter	na	na
	300 lx	Fair	--	--	--	--	Higher	Brighter
	150 lx	Poor	--	--	Lower	--	Higher	Brighter
Ventilation rate	60 m^3/h	Good	Higher	Fresher	Higher	Fresher	na	na
	30 m^3/h	Fair	Higher	Fresher	--	--	Higher	Fresher
	0 m^3/h	Poor	--	--	Lower	Stuffier	Higher	Fresher

a: "--" indicates not significantly different; "na" means not applicable.

4.1 The impact of parameter values

The subjects were able to detect changes in temperature, sound pressure and illuminance without external information: their sensation and satisfaction changed significantly as these parameters varied when they were blinded to the conditions. Providing subjects with the values of these parameters did not significantly impact their perceptions of thermal, acoustic, and visual environment conditions.

In contrast, the subjects did not perceive changes in ventilation rate when they were not informed of the conditions. The hypothesis is that the subjects' perceptions that the room was not well ventilated even as the actual ventilation rate changed could have resulted from the windows in the room being closed and covered during the tests. As a result, information about the ventilation rate value significantly improved their perceived IAQ.

4.2 The impact of ratings

Providing subjects with a rating of the controlled environment more frequently yielded a significant effect on their sensations and satisfaction compared to informing them of the parameter values. This effect was found not only for IAQ but also for the other three environmental factors. Except for the thermal environment, the subjects reported significantly worse satisfaction and/or sensations after they were informed that an aspect had Poor quality. Only when they were informed that the IAQ rating was Good did their satisfaction improve and they perceived the indoor air to be fresher. The Fair rating yielded an increase in thermal satisfaction and a decrease in acoustic satisfaction relative to no information. In this study, ratings of Good, Fair and Poor were assigned to each level of the controlled environmental parameters based on Chinese standards and design codes. However, the association of the subjects with these terms and environmental conditions could be different than the standard. For environmental monitoring systems or instruments that provide ratings of the measured environment either in words or colors, extra attention should be paid to specifying the range of the parameter values for each rating. Different settings may have diametrically opposed effects on building occupants' perceptions.

4.3 The impact of values and ratings that are better than actual conditions

When the subjects were presented with parameter values and ratings that were better than the actual conditions, their sensation and satisfaction were, in most cases, more favorable than when the same conditions were presented with the true parameter values and ratings. These results indicate that perceptions of the environment can be manipulated by misinformation. Notably, when more favorable information was provided, perceptions of the actual lower-quality conditions were in some cases similar and in other cases not as good as when the same group experienced the better conditions in reality (Table A.5). For example, acoustic satisfaction was significantly lower when the subjects experienced 45 dBA and were told that the acoustic environment was 40 dBA and Good than when they experienced 40 dBA and were correctly informed that the condition was 40 dBA and Good. Since downgraded ratings and values were not used in this study, more research is needed to evaluate whether downgraded ratings and values would have a negative impact on perceptions.

To prevent the subjects from being skeptical about the information provided, as a control, the provided better information was not far from the actual environmental condition. The subjects were not informed that the controlled environment was Good when it was actually Poor. Another question pertains to people's response when receiving information that is very different than their sensation: how many will question the accuracy of the information, and will the influence of any information provided be reduced?

While this study found that the subjects' satisfaction could be improved with better information, intentionally providing inaccurate information with the intent of manipulating satisfaction is unethical and should not be done.

4.4 Contribution of this study

This study provides an original contribution to the literature with experimental data on occupants' perceptions of IEQ when they were informed of various environmental measurement information. The unanswered question of how the widespread use of indoor environmental monitoring systems actually affects building occupants was addressed. The main contributions of this study are as follows:

1. The results of this study confirmed that occupants' perception of IEQ is not merely a physiological but also a psychological response. When occupants receive different information about environmental conditions, their sensation and satisfaction with IEQ factors could be significantly different under the same conditions.

2. The findings of this study have implications for devices and platforms that provide information on indoor environmental conditions and for studies of satisfaction with aspects of IEQ. For example, the subjects tended to rate IAQ negatively when the windows were closed and they were not aware of the operation of a mechanical ventilation system. Therefore, providing information on ventilation conditions (value or rating), especially when natural ventilation is unavailable, is highly recommended, as it may improve occupants' perception of IAQ.

3. The results of this controlled study suggest that in situ studies of environmental perception should take care to note the information that is available to occupants who are asked to complete subjective surveys. The impact of environmental information could be mistakenly identified as an individual difference if the source presenting the information is not considered in the analysis.

5 Limitations

The major limitation of this study is the subject sample. All of the subjects were undergraduate or graduate students, and the majority had backgrounds in disciplines related to engineering. While the impact of their educational background on their environmental perception was investigated and no substantial impact was found, other contextual factors that have been found to influence IEQ perception, such as age [43–45] and exposure history [46–50], still limit the findings of this study to a narrow population. Environmental information may have different impacts on other groups. Since all the subjects were Chinese, the Chinese standards were followed when designing the experimental conditions. The results obtained in this study are plausibly dependent on the specific conditions used, and even the same conditions could produce different results for subjects acclimated to different indoor conditions.

The other limitation is that the subjects were exposed to multiple indoor environmental conditions in a fixed sequence within a single day. Whether any of the subjects learned the exposure sequence and were influenced by it could not be determined. Due to constrained resources, continuous exposure has more often been adopted in similar studies [51–54]. It is possible that different results could be obtained by changing the sequence of the exposure or testing only one condition each day. In addition, the adaptation of the subjects to the indoor environment is an issue worth exploring but was not investigated in this study [55,56]. The frequency at which the subjects checked the video display was not observed or recorded. The different attention that the subjects paid to the provided environmental information may have influenced their reactions. As this study was conducted under highly controlled conditions, the translation to variations occurring under natural conditions is necessarily uncertain.

6 Conclusions

To study how various environmental information influences occupants' perceptions of IEQ, three distinct groups, each with 16 subjects, were exposed to 12 controlled indoor environmental conditions, and each group was provided with two different types of environmental information from among the following: no information, parameter values, ratings, accurate values and ratings, and better-than-actual values and ratings. Their sensation and satisfaction with environmental factors, including the thermal environment, acoustic environment, visual environment and IAQ, were collected using a questionnaire. The main conclusions are as follows:

- Information in the form of parameter values did not significantly impact perceptions of the thermal, acoustic or visual environment, whereas the sensation and satisfaction with IAQ were significantly improved after the subjects in one group were informed of the per-person ventilation rate.
- Information on environmental ratings more frequently yielded a significant impact on subjects' perceptions of the thermal, acoustic, and visual environments and IAQ than information on parameter values. The subjects were more sensitive to information about Poor or Fair ratings than to

information about Good ratings. A Poor rating sometimes reduced satisfaction, while a Fair rating had either a positive or negative impact.

- Misinforming the subjects that the conditions were better than they actually were significantly improved their satisfaction under most environmental conditions. However, such improvements were often less and never greater than those in an environment that was actually better.

The findings of this study provide insights into the underexplored question of how perceptions of indoor environmental conditions may be impacted by external information. The findings suggest value in further exploration of this field of study using larger and more diverse populations and considering additional variations in the mode of information provision.

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