Investigating Indoor Environmental Quality Using Virtual Reality In Climate Chambers

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Abstract

Various phenomena defining the perception of indoor environmental quality have been proven to directly or indirectly affect one and another. However, there are no extensive studies on whether there are interactions between occupants' thermal sensation and their perception of the view-out. To investigate this potential interrelationship, a semi-controlled 4 x 4 cross-over experiment involving 51 subjects (25 male, 26 female) was designed. The experiment was conducted in a climate chamber, where thermal condition scenarios could be strictly controlled, while the view-out scenarios were simulated using virtual reality (VR). A digital interactive questionnaire inside the VR environment was used to record subjects' thermal sensation and view-out satisfaction during the experiment. The results showed that view-out satisfaction may be more sensitive to indoor thermal conditions in rooms with moderate level of glazing compared to rooms with a high level of glazing; in rooms with high level of glazing subjects may be more forgiving towards overheating due to high view-out quality. Overall, the experiment has demonstrated that using VR in climate chambers is a promising approach for investigating interactions between the visual and indoor climate aspects.

1. Introduction

Indoor environmental quality is a subjective human conviction based on a multi-sensory experience of the space. There are many theories on how various visual phenomena and indoor climate aspects affects the perception of indoor environmental quality. These theories are to a wide extent developed under the assumption that an individual phenomenon or aspect can be investigated and theorized upon independently, i.e. assuming that there is no or little interactions between the various phenomena or aspects. Examples of this are thermal comfort models like Fanger's model [1], the adaptive comfort model [2], glare models like daylight glare probability DGP [3], and models for view-out quality and privacy [4]. Investigations on how indoor environmental quality phenomena and/or aspects interacts with one another are relatively rare but not absent. Early examples includes e.g. how room colors may affect the perception of thermal comfort and how air temperature, relative humidity and air movement (three parameters also affecting thermal comfort) may affect the perception of indoor air quality. However, to the best of our knowledge, there has not been any attempts to investigate whether indoor thermal conditions may affect the perception of view-out quality. This paper reports on an experiment investigating whether view-out satisfaction is affected by the indoor thermal conditions, and whether indoor thermal conditions influence the subjective notion of the property price.

2. Method

The experiment was conducted in a climate chamber where thermal conditions could be strictly controlled while the view-out scenarios were simulated inside the climate chamber using virtual reality (VR). The following sections briefly describes the scenarios what was investigated, the setup in the climate chamber and the VR models, the questionnaire used for subjective assessment of the scenarios, and the experimental design.

2.1 Description of scenarios

A total of four scenarios were defined as depicted in figure 1. The scenarios were combinations of two different thermal conditions where only the operative temperature was different while relative humidity and mean air velocity was were kept constant (RH=40%, mean air velocity=0.1 m/s), and two different window sizes. We also tried to simulate radiation from direct sun using heat lamps but this aspect was disregarded as tests revealed that the functionality of the VR goggles could not withstand the radiation heat. All subjects in the experiment had a clothing insulation level of 0.7 clo and an estimated activity level of 1.2 met. Consequently, the PMV=0.39 for scenario A and C and PMV=1.85 for scenario B and D. Air change rate was set constant at 10 l/s per person.

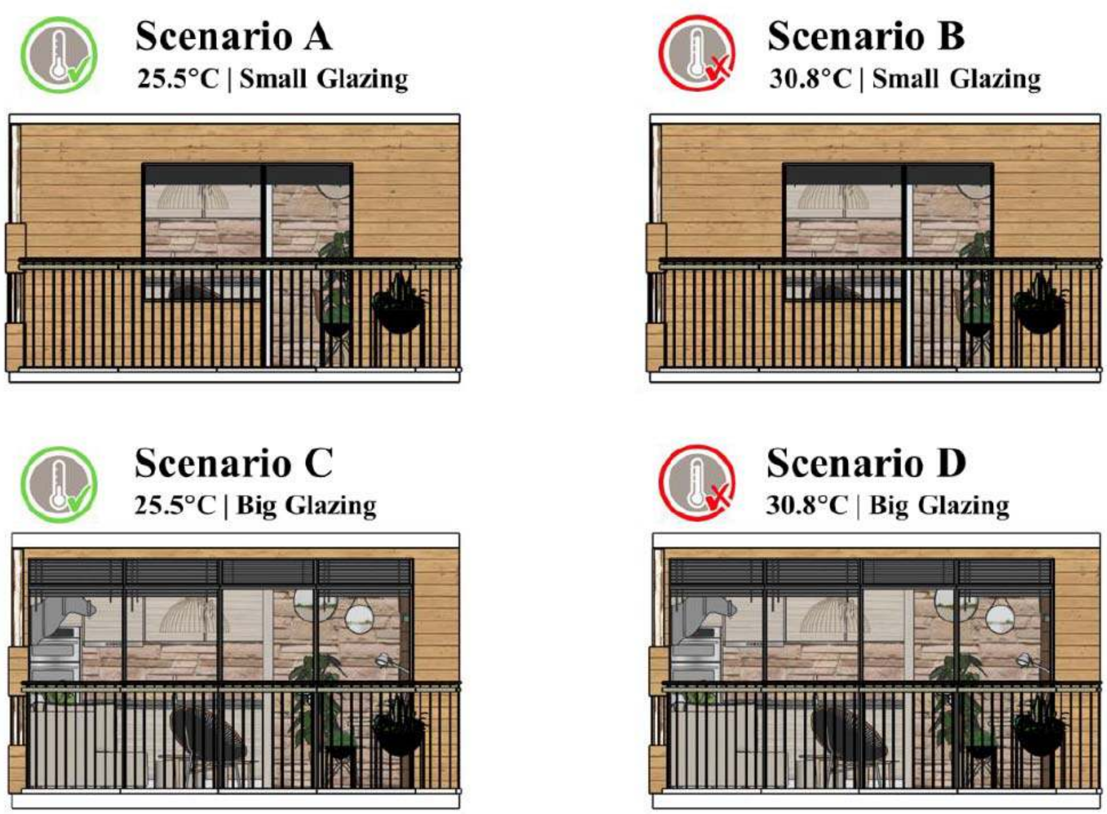
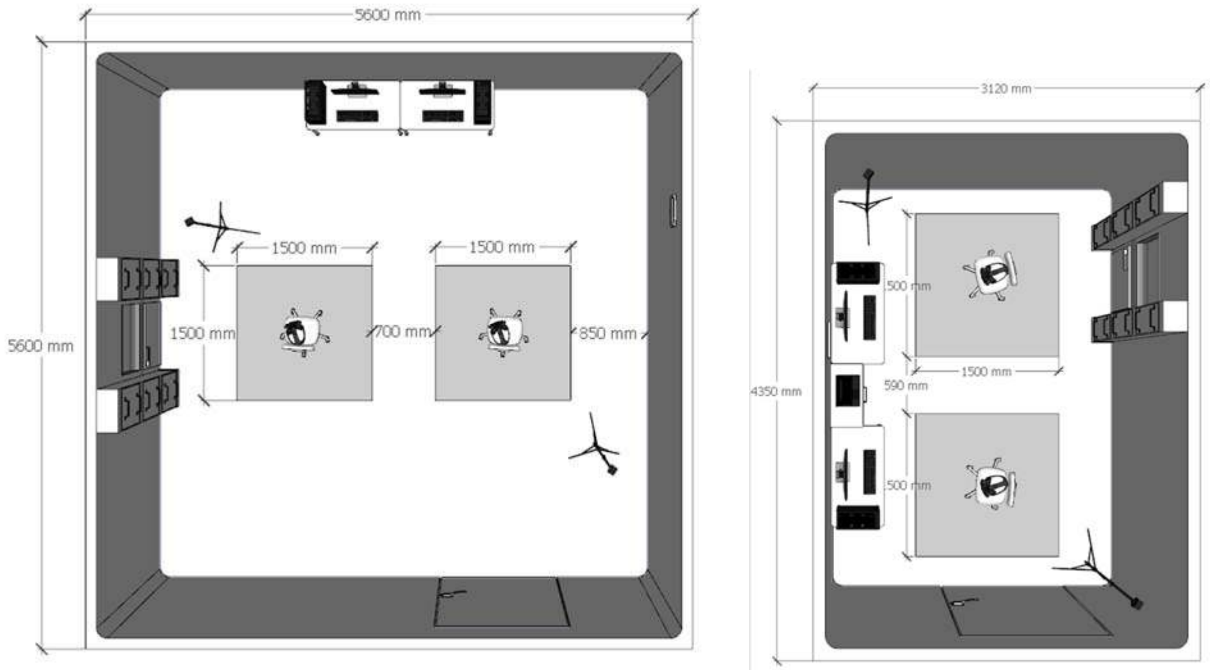


Figure 1: The four investigated scenarios. Two different operative temperatures combined with two different glazing sizes.

2.2 Climate chamber and VR models

The experiment took place in the two climate chambers located at the department of Public Health at Aarhus University, Denmark. The climate chambers are steel cladded chambers with a high-precision HVAC&R system. Each chamber room was equipped with VR systems to hold two participants at the same time. The setup is illustrated in figure 2.



.Figure 2: Illustration of climate chamber and VR setup.

The basic 3D model for the virtual reality environment was build and designed in SketchUp. This model was imported into the game development platform Unity, where the surrounding environment was generated, and the questionnaire programming were written. Subjects were sitting down during the whole experiment for security reasons but could move around inside the virtual environment using a teleportation function. Figure 3 depicts examples of the VR environment.

Figure 3: Illustrations from the VR environment. Left: Large glazing area. Right: Moderate glazing area.

2.3 Questionnaire

Questions were formulated and votes could be casted by subjects directly in the VR environment using visual analogue scales like the one shown in figure 4. Table 1 summarizes the visual analogue-scaled questions asked in each scenario of the experiment. View-out questions were asked for a VR seating position in the couch near the window and at an office desk in the back of the room.

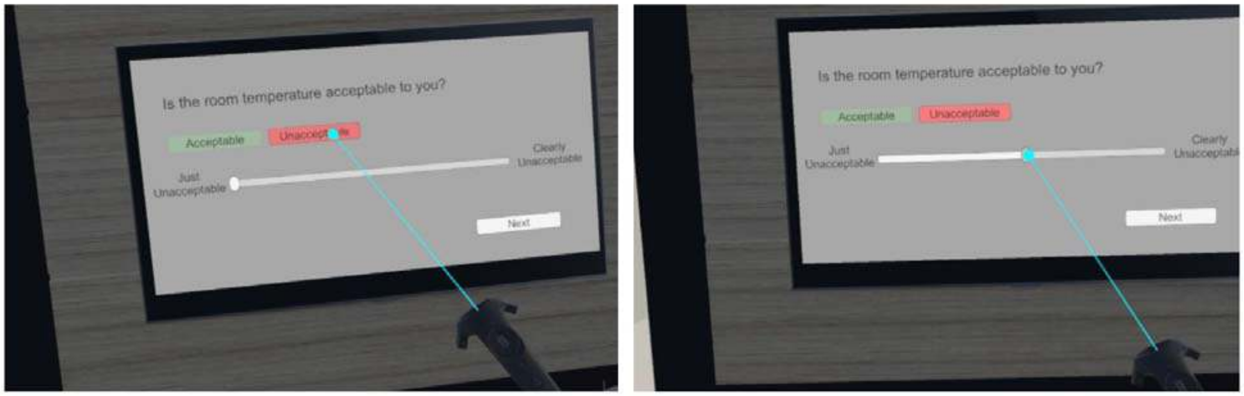


Figure 4: Thermal acceptability question. Left: Pressing 'unacceptable' using the controller pointer. Right: Moving unacceptable slider using the controller pointer to determine the degree of unacceptability.

Table 1: Question scales used in the experiments.

Name	Questions Types	Voting scale
Thermal Comfort	– Initial thermal satisfaction	Acceptable – Unacceptable Just acceptable – Clearly acceptable Just unacceptable – Clearly unacceptable
	– Initial thermal sensation	Very cold – Very hot
	– Adapted thermal satisfaction	Acceptable – Unacceptable Just acceptable – Clearly acceptable Just unacceptable – Clearly unacceptable
	– Adapted thermal sensation	Very cold – Very hot
	– Adapted thermal sensation of body parts (head, torso, feet)	Very cold – Very hot
	– Temperature estimation	Min 15°C – Max 35 °C
View Quality	– Price estimation	Very cheap – Very expensive
	– Spacious rating	Constricted – Spacious
	– View quality voting from different positions (desk and coach)	Satisfied – Unsatisfied Just satisfied – Clearly satisfied Just unsatisfied – Clearly unsatisfied

2.4 Experimental design

A total of 51 subjects (25 males and 26 females) participated in the 4x4 randomized crossover-designed experiment. In this crossover design, subjects will experience all four scenarios described in previous section, and all subjects will be exposed to the same number of scenarios making the experiment balanced. As a part of the randomization procedure, 4x4 sequences of the scenarios was generated using the Williams Latin square. The order of questions that the subjects should answer during the experiments might be a potential bias in the experiment. Therefore, the questions described in the previous section were divided into two categories: questions related to the thermal comfort (T) and questions about to the view-out (V). Two orders of questions were then established, namely “TV” (subjects receiving thermal questions before view questions) and “VT” (subjects receiving view questions before thermal questions). We then assigned VT and TV to two similar scenario sequences leading to eight different sequences.

Each participant was randomly assigned to a certain sequence of scenarios using a lottery system that made sure that all sequences were executed an approximately equal amount of times. Once assigned a sequence, a subject would go through a VR training session in the preparation room to get initial experience with the technology including how to answer questionnaires inside the VR environment before starting the actual experiment. The subject then went to the climate chamber and had to stay there for 15 minutes to adapt to the thermal condition (30 minutes would have been preferred but that would have increased time consumption for the experiments significantly increasing risk of survey fatigue). The subject then used approx. 5 minutes to answer the questionnaire leading to a total session time of 20 per scenario. The subject then went back to the preparation room and spent a washout period of 20 minutes before entering the next scenario in an attempt to reduce any carry-over effect between scenarios.

3. Results

The results regarding the question regarding view-out satisfaction is illustrated in figure 5 and 6. There is a tendency that the hot indoor temperature affected the view-out satisfaction more in the setting with moderate glazing area compared to the setting with large area.

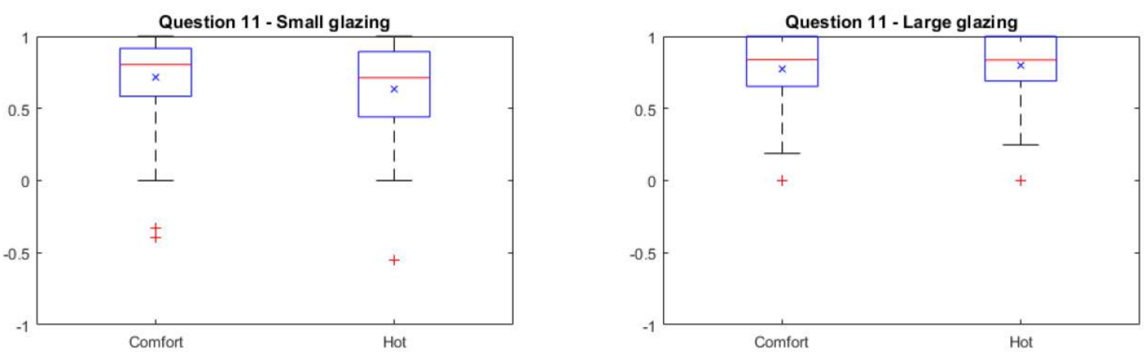


Figure 5: View-out satisfaction from office desk in the back of the room

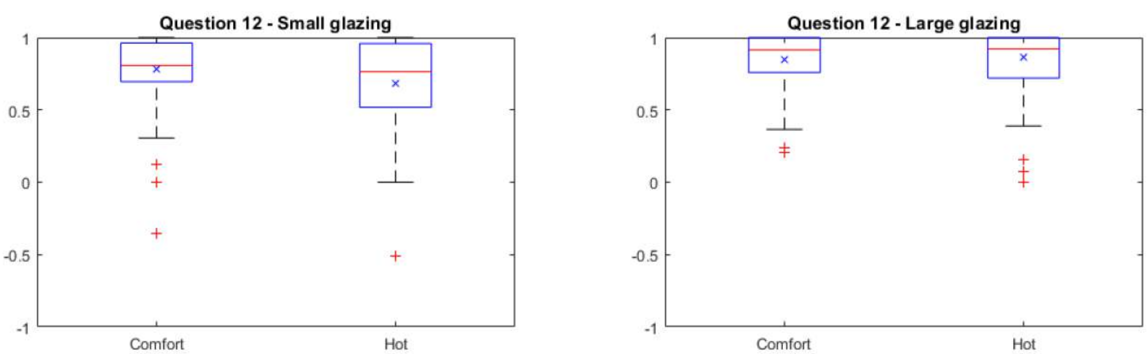


Figure 6: View-out satisfaction from couch near the window.

The votes on the subjective notion of the property price for each scenario is illustrated in figure 7. There is a tendency that the subjects found the apartment with large glazing to be more expensive than the apartment with moderate glazing no matter the thermal condition. For the large glazing area, there is also a tendency that the price was voted higher in the comfort condition.

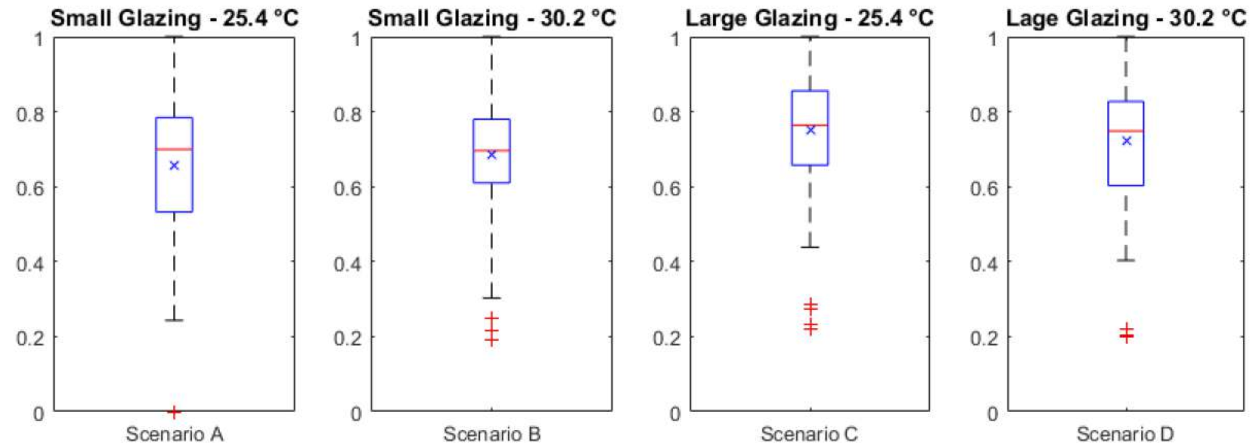


Figure 7: Subjective vote of property price for the four scenarios.

4. Conclusion

The investigation led to the following conclusion: For a moderate glazing size, the subjects tend to be more satisfied with the view in a comfort thermal condition than an overheated condition. The indoor temperature did not seem to affect the perception of view-out in the scenario with large glazing area. None of these tendencies were statistical significant. In addition, the subjective notion of property price seems unaffected by the thermal condition.

Overall, the experiment has demonstrated that VR in climate chambers is a promising approach for investigating interactions between the visual and indoor climate aspects that together defines indoor environmental quality. Future studies should investigate the significance of the quality of the surrounding outdoor environment, as the view in this study in general was rated very high no matter the scenario indicating that the surroundings were too nice to be affected by temperature and/or window size.

References

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