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Does thermal control improve visual satisfaction? Interactions between occupants' self-perceived control, visual, thermal, and overall satisfaction

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Abstract

Occupants' satisfaction had been researched independently related to thermal and visual stimuli for many decades showing among others the influence of self-perceived control. Few studies revealed interactions between thermal and visual stimuli affecting occupant satisfaction. In addition, studies including interactions between thermal and visual stimuli are lacking different control scenarios. This study focused on the effects of thermal and visual factors, their interaction, seasonal influences, and the degree of self-perceived control on overall, thermal, and visual satisfaction. A repeated-measures laboratory study with 61 participants running over two years and a total of 986 participant sessions was conducted. Mixed model analyses with overall satisfaction as outcome variable revealed that thermal satisfaction and visual satisfaction are the most important predictors for overall satisfaction with the indoor environment. Self-perceived thermal control served as moderator between thermal satisfaction and overall satisfaction. Season had slight influence on overall satisfaction. Random effects explained the highest amount of variance, indicating that intra- and interindividual differences in the ratings of satisfaction are more prevalent than study condition. Future building design and operation plans aiming at a high level of occupant satisfaction should consider personal control opportunities and take into account the moderating effect of control opportunities in multimodal interactions.

KEYWORDS
combined effects, occupant behavior, perceived control, thermal comfort, user satisfaction, visual comfort

Practical Implications

- Thermal and visual satisfaction are not independent, but affect each other. Therefore, complaints regarding one domain may be caused by dissatisfaction in the other domain. Consequently, it is advisable that investigations regarding the cause of complaints consider multiple domains in question.
- Individual control increases thermal satisfaction and is also moderating the interaction between thermal satisfaction and visual satisfaction on overall satisfaction. Hence, increasing,

for example, thermal control options affects not only thermal but also overall satisfaction with indoor environmental conditions.

- To account for the intra- and interindividual differences in self-perceived thermal control, future buildings should put users into a position in which they have as much control as possible over thermal and visual conditions to increase satisfaction, for example, to install easy-to-use thermal controls to improve thermal satisfaction.
- Further studies and careful methodological considerations are necessary before improvements in the design of the indoor environment can be suggested, for example, dynamic lighting adjusted to thermal conditions or vice versa to contribute to energy savings.

1 | INTRODUCTION

Human beings are continuously exposed to multiple indoor environmental exposures from different domains at the same time. These domains include thermal and visual stimuli leading to a perception of thermal or visual comfort. Thereby, thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment".[1] Visual comfort means "a subjective condition of visual well-being induced by the visual environment".[2] The overall evaluation of perceptions from different domains leads to a level of overall satisfaction with indoor environmental conditions.

1.1 | From single to multidomain studies

Occupants' satisfaction had been researched independently related to thermal and visual stimuli for many decades.[3-6] In contrast, multidomain studies, for example, considering thermal and visual aspects and their interaction, are scarce.[7,8] Following the definition by Torresin et al, these multidomain approaches can be distinguished into crossed (main) effects and combined effects. Combined effects are defined as the effects of two or more distinct domains, for example, thermal and visual, on a third domain, for example, overall satisfaction. In contrast, crossed effects are analyzing a main effect from one domain, for example, thermal stimuli, on another domain, for example, visual perception. A recent review on multidomain studies came to the conclusion that results from multidomain studies are not conclusive and partly contradictionary. Related to thermal and visual conditions, inconsistent results related to the existence or direction of an interaction exist and depend on lighting conditions (illuminance level, intensity, and spectrum) and outcome measure (thermal sensation vs. thermal comfort).[8]

Relevant for the study presented here is the current state of knowledge related to combined effects on overall satisfaction, crossed effects on thermal and visual satisfaction, and the influences of perceived control and season.

1.2 | Combined effects on overall satisfaction

Related to combined effects, Alm et al and Clausen et al modeled overall satisfaction with room conditions based on single-domain conditions.[9,10] Huang et al[11] and te Kulve et al[6] stated that overall satisfaction is affected more by temperature or noise compared with lighting. Frontczak et al found highest correlations between overall satisfaction and satisfaction with temperature.[12]

1.3 | Crossed effects on thermal and visual satisfaction

With respect to crossed effects, Chinazzo et al[13] investigated the effect of daylight transmitted through three colored glazing types (blue, orange, and neutral) on thermal responses and overall comfort, at three temperature levels (19°C, 22°C, and 26°C). Statistical analysis revealed a color-induced thermal estimation, independent of temperature levels: With a blue glazing, people felt colder and less comfortable than with a neutral one. With an orange glazing, people felt warmer and more comfortable than with a blue one. The same authors also investigated the effect of daylight illuminance levels (~130 lux, ~600 lux, ~1400 lux) on thermal responses under three temperature levels (19°C, 23°C, and 27°C) and found a cross-modal effect of daylight on thermal responses.[14] According to Huang et al,[11] occupants judged their environment as thermally acceptable even when they are dissatisfied with lighting levels. Nicol and Humphreys[15] found that lighting use decreases with increasing indoor and/or outdoor temperatures. Lighting exposure can alter thermal comfort or thermal sensation: Some studies found an effect of light intensity on thermal sensation but not on thermal comfort (eg, [16,17]), while others found the opposite direction.[18]

Despite crossed and main effects of individual domains, the **level of perceived control** was shown to influence satisfaction with temperature (eg, [19,20]). According to Brager et al,[21] study participants with different degrees of control—even when they experienced the same thermal environment, activity, and clothing levels—had significantly different thermal responses, though their field study design does not permit a distinction between individual differences and differences in perceived level of control. Kwon et al[22] asked persons working in offices in the Netherlands about perceived satisfaction with control, thermal, and visual room conditions. Findings suggested that higher controllability led to more satisfaction. Raja et al[23] stated that control over blinds and curtains can improve thermal comfort. Newsham[24] found that manual control of blinds and electric lighting

can lead to better thermal comfort. In summary, experiencing and/or having control over room conditions improves overall, thermal, or visual satisfactions and overall satisfaction. These interactions are found in some studies[19,25-27] but not in others.[28-30] At the same time, recent reviews showed that studies analyzing interactions between thermal and visual influences on levels of satisfaction, which are dominantly performed within laboratory environments, rarely permit participants to control their thermal and/or visual stimuli.[7,8] Torresin et al identified solely the study by Pellerin and Candas,[31] which permitted participants control over stimuli in experimental studies dealing with multimodal interaction.

1.4 | Seasonal influences

In addition, studies on the interaction between thermal and visual comfort mainly focused on a limited number of seasons (summer preferred), or the study participants were exposed to the experimental conditions for different time periods.[32] At the same time, the authors expect seasonal influences on the interaction between thermal and visual stimuli due to differences in their appraisal. For example, warm conditions appeared more preferable in winter compared with summer[33] and there is a preference for higher illuminance levels and higher glare acceptance in spring compared with autumn and winter.[34]

1.5 | Research objectives and approach

In order to overcome these identified gaps in the literature, the overall objective of this study was an increased understanding of interactions between visual and thermal stimuli and their effect on thermal, visual, and overall satisfaction with room conditions under different control scenarios and different seasonal influences.

In detail, the specific objective of our study was testing the conceptual model shown in Figure 1 representing the hypothesized relationship between thermal and visual stimuli and thermal satisfaction, visual satisfaction, and overall satisfaction with season and self-perceived control as moderators. According to our knowledge, this is the first study looking at the effect of control on interactions between thermal and visual stimuli in semi-standardized laboratory experiments in all of the four seasons. On this basis, we conducted an experimental repeated-measures study systematically varying
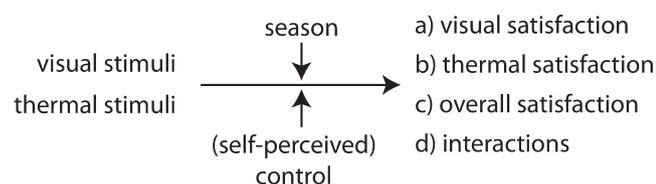

FIGURE 1 Conceptual model underlying the analysis of this study

thermal and visual stimuli together with the level of control among four seasons.

2 | MATERIALS AND METHODS

2.1 | Experimental facility

This study was conducted in the LOBSTER facility (http://lobster-fbta.de, [35,36]), a free-standing experimental building with two fully equipped offices and two workplaces each. The room air and surface temperatures can be controlled individually. The HVAC system enables operative room temperatures from 15 to 35°C with homogenous distribution of the surface temperature of the walls. The color of indoor walls is white. Artificial lighting is provided by suspended luminaires, which have a direct part and an indirect part that can be dimmed separately. The sensors installed allow capturing physical parameters of the room and states of windows and doors (eg, if windows are open, closed, or tilted). Physiological parameters of the participants (eg, heart rate, skin temperature, skin moisture, and skin conductance level) were also measured but not analyzed here.

2.2 | Experimental protocol

The basis of the experimental protocol was a repeated-measures design for which participants were surveyed up to four seasons and six different thermal and visual conditions each.

In the years 2016–2018, two distinct age-groups were invited: young (aged 18 to 32 years) and older (aged 50 to 70 years). Two distinct age-groups have been chosen in order to include not only young and healthy university students and thereby increase the generalizability of results. Including an older age-group is meaningful, because existing literature suggests that age affects thermal[4,5] and visual[37] perception.

The six conditions were characterized by either thermal or visual conditions being fixed and the other conditions being controllable by the participants as presented in Table 1. In the Tx conditions, the temperature range was fixed, while visual conditions controllable by participants. In the Vx conditions, participants were able to adjust the temperature set point according to their preferences, while illuminance levels were fixed. It should be noted that in none of the conditions, control over visual/thermal conditions was completely removed: Participants were still able to change their clothing, tilt the window, or change their head/working position in relation to the façade. Therefore, the perceived level of control was assessed and included in statistical analysis rather than the control condition (see below). In addition, in order to reduce repetitions for participants and due to previous results showing a large difference to conditions without any control opportunity,[38] no conditions with both fixed temperature and illuminance levels were introduced.

The repeated-measures design was chosen to reduce the variance due to interpersonal differences. Participants were invited

to the LOBSTER facility for four days in each of the four seasons (Figure 2). Participants performed two sessions per day, leading to eight sessions per season. In each session, one of the six above described conditions was performed. The order of the six conditions was randomly assigned to each participant in every season. Therefore, a condition was either conducted in the morning or afternoon. The two additional sessions created by the difference from the six conditions and eight sessions were added in order to counterbalance daytime effects by repeating two of the six conditions at different times of the day. Therefore, each participant conducted per season one of the three T conditions and one of the three L conditions for a full day. A complete participation would lead to 16 days x 2 sessions a day = 32 measuring points in 24 different conditions (six experimental conditions multiplied by four seasons).

TABLE 1 Characteristics of the six distinct study conditions. Thermal and visual experimental stimuli were either predetermined and not modifiable by participants (eg, 20°C in condition T1) or subject to participants' preference (eg, thermal stimuli in condition L1)

Condition	Setting for thermal environment	Setting for visual environment
T1	Fixed at approx. 20°C	Artificial lighting and exterior blinds controllable by participant
T2	Fixed at approx. 25°C	
T3	Fixed at approx. 30°C	
L1	Temperature set point controllable by participant	Fixed at approx. 300 lx
L2		Fixed at approx. 500 lx
L3		Fixed at approx. 1000 lx

On the first day, the participants received instructions regarding the schedule, room characteristics, and control opportunities (light, thermostat, external blinds; depending on test condition), and written informed consent was obtained. Then, sensors for skin conductance level, skin temperature, and heart rate were applied. Note that analysis of physiological data is not included here. After entering one of the experimental office rooms, the participants had to fill in the first questionnaire. Questionnaires started automatically at different time points in the morning, before, and after lunch break, and in the afternoon (see 2.3 for further details). Between answering the questionnaires, the participants were allowed to work on their own projects, research on the Internet, or read a book. The participants had to leave the LOBSTER after the first session lasting about 3 h for a 30-min lunch break. Afterward, they had to change the room and work in the other room for the second session lasting another 3 h.

The experimental protocol and data collection material were approved by the Ethics Commission of Karlsruhe Institute of Technology including clearance by the data protection officer of Karlsruhe Institute of Technology and are according to the Declaration of Helsinki.

2.3 | Data collection

Date collection included physical parameters, questionnaire items, and physiological data as described in the following.

2.3.1 | Physical data

The list of sensors and their accuracy is presented in Table 2, their position in Figure 3. With respect to the visual parameters, the horizontal illuminance level was measured at every workplace 1.90 m
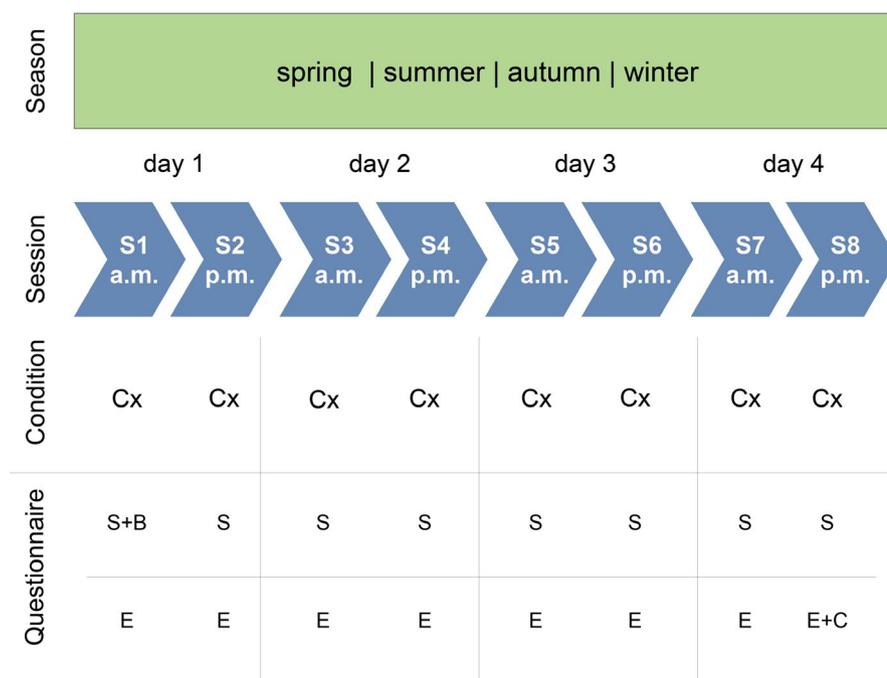

FIGURE 2 Study design for one participant in all conditions and every season. Sx—one day is divided into two sessions of three hours each. In total, there are eight sessions in each season. Cx—each participant experiences all six distinct conditions (L1-L3 and T1-T3) in the four days of participation. Two conditions were experienced twice each season. S—start survey; B—background survey; E—end survey; C—concluding survey

away from the window next to the keyboard at desk level (0.75 m height). Additionally, radiation intensity and illumination level (horizontally) were measured in the middle of the room on the desk at a height of 0.92 m and at a distance of 1.75 m from the window. A luminance camera placed in the back of the room 1.25 m away from

the rear wall at a height of 1.2 m (lens center) and facing the window façade measured the luminance distribution of the room and the window via taking a photograph every 5 min with a so-called "fisheye-lens" offering 180° angle of view. These photographs were then converted into luminance pictures.

Thermal properties were measured adjacent to the workplaces close to the middle of the room, that is, 2.7 m from the window, and included air temperature, globe temperature, relative humidity, and air velocity. Operative temperature (T_{op}) was derived from air temperature and radiant temperature of which the latter was based on adjusting globe temperature by air temperature and velocity. Indoor Air Quality (CO_2) was constantly monitored, and the ventilation rate was adjusted to keep CO_2 levels below 1000 ppm in order to minimize confounding influences between perceived Indoor Air Quality and thermal perception known from previous studies.[8]

Outdoor sound-level measurement was captured below the building in the open space between building and ground level (note that the laboratory is elevated). Measures of outdoor climate such as outdoor temperature, horizontal global solar radiation, outdoor illuminance, brightness, and wind parameters were collected with a weather station on top of the building.

2.3.2 | Questionnaires

The participants had to respond to four different questionnaires (start and end, background, and conclusion) on the computer.

TABLE 2 List of sensors and their accuracy

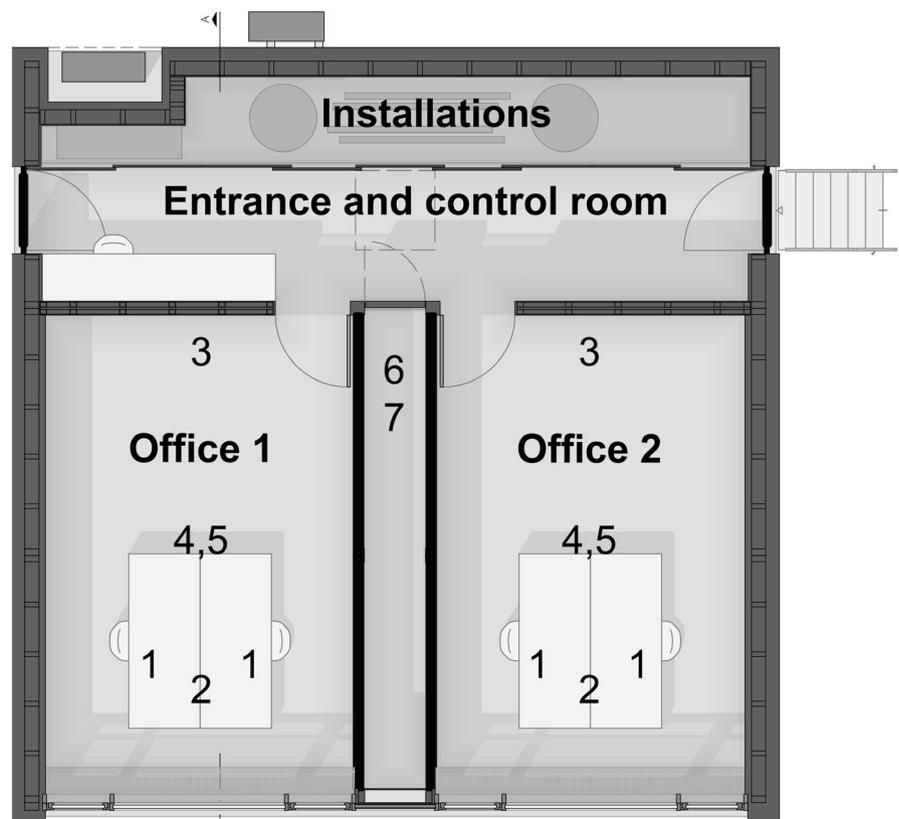| ID[a]	Measurement	Quality
1	Horizontal illuminance level (luxmeter)	Total error 7% (class B)
2	Radiation intensity and horizontal illuminance level (specbos)	Accuracy 2%
3	Luminance (luminance camera)	Measurement uncertainty ~7%
4	Air temperature, globe temperature, relative humidity, air velocity	Accuracy ±0.2 K, ±(0.30 K + 0.005 × T), ±2.0% and ±(3% measured value + 0.01)
5	Carbon dioxide (CO_2)	Accuracy ±3%
6	Outdoor temperature, relative humidity, horizontal global solar radiation, outdoor illuminance, wind direction, wind speed	Accuracy ±0.1 K, ±2.0%, ±0.2%, ±2%, ±5°, 3%
7	Outdoor sound level	Accuracy ±1.4 dB

[a]See Figure 3 for position of sensor.

FIGURE 3 Layout of laboratory and position of sensors. Note: Numbers correspond with ID listed in. Sensor 6 is positioned at the top of the roof and sensor 7 in the space below the building

The start questionnaire was due in the morning after entering the office and right after the lunch break. This questionnaire includes questions about thermal and visual perception and satisfaction with lighting, temperature, general room conditions, self-perceived thermal control, global thermal sensation, thermal preference, thermal acceptance, evaluation of comfort, sensation and air velocity, air moisture, and direct and indirect glare.

In the corresponding literature regarding thermal and visual satisfaction, these ratings are usually assessed by different scales (eg, a 4-point scale in thermal, but a 5-point scale in visual comfort research). In order to harmonize ratings, thermal, visual, and overall satisfaction was assessed by visual analogue scales (VASs) (Table 3).

The end questionnaire had to be filled right before lunch break and before leaving the LOBSTER in the late afternoon. This questionnaire consists of the same questions like the start questionnaire and additionally asked about activities in the past three hours in the office room.

The background questionnaire consists of items related to influencing factors on comfort sensation such as body height, weight, sex, age, clothing degree, quality of sleep, thermo-specific self-efficacy, and thermal and visual preferences.

The concluding questionnaire was collected from the participants at the end of last day of their participation in each season. This questionnaire includes the same items as the end questionnaire together with three scales of the NEO-FFI[39]: extraversion, neuroticism, and openness.

During the day, the participants were asked to push one of several buttons on the computer when they drink something or when they change something on their clothes. The corresponding information was not included in the analysis.

Age-group was assessed beforehand, defining "young" as people aged 18 to 32 years and "older" aged 50 to 70 years. Sex was assessed when participants started the questionnaire.

2.4 | Participants

In total, $N = 61$ participants took part in the study of which 25 (41.0%) were 50 to 70 years old, 33 (54.1%) were male, and 32 (52.5%) were wearing glasses. The amount of conditions completed per participant ranged from $N = 2$ to $N = 36$. The number of participants who completed all six conditions each in all seasons, that is, 16 days a year and a total of 32 conditions, was 7 (14.8%). The number of participants who experienced all six conditions but not in every season was 44 (72.1%).

2.5 | Analysis methods

Analysis software packages were SPSS (IBM SPSS Statistics, Version 25, IBM Corp. 2017) and RStudio (Version 1.1.456, R Development Core Team, 2012), an open-source software application for R.

Mixed Models[40] packages lme4 and lmeTest of R[41] were used to analyze the data, because they can handle unequal repetitions among participants caused by missing sessions.[42] Images were generated via packages ggplot2,[43] fields,[44] and lsr[45] of R. xy plots (R-package

TABLE 3   Items used to assess participants' overall, thermal, and visual perception and self-perceived thermal control. Original German versions along with translations into English are shown. Visual analogue scales were applied for these questions in the form of continuous lines with verbal anchors at the left and right ends of the line and no numbers. Participants could choose any position on the line for their response. Chosen positions were coded into continuous numbers for analysis. The order of appearance in the questionnaire was self-perceived control, visual, thermal, and overall satisfaction

Variable	Question	Verbal anchors and coding[a]
Overall satisfaction (ov.sat)	Overall, how dissatisfied or satisfied are you right now with the general conditions (workplace environment, visual conditions, room climate, furniture, appearance) at this workplace? *Alles in allem, wie unzufrieden bzw. zufrieden sind Sie im Moment mit den Gesamtbedingungen (Arbeitsplatzumgebung, Lichtverhältnisse, Raumklima, Möblierung, Gestaltung) an diesem Arbeitsplatz?*	Very dissatisfied (−50) | very satisfied (+50) *Sehr unzufrieden (−50) | sehr zufrieden (+50)*
Thermal satisfaction (therm.sat)	How dissatisfied or satisfied are you right now with the thermal conditions in this room? *Wie unzufrieden bzw. zufrieden sind Sie mit den thermischen Bedingungen in diesem Raum?*	Very dissatisfied (−50) | very satisfied (+50) *Sehr unzufrieden (−50) | sehr zufrieden (+50)*
Visual satisfaction (vis.sat)	How dissatisfied or satisfied are you right now with the visual conditions (brightness, glare) in this room? *Wie unzufrieden bzw. zufrieden sind Sie mit den Lichtbedingungen (Helligkeit, Blendung) in diesem Raum?*	Very dissatisfied (−50) | very satisfied (+50) *Sehr unzufrieden (−50) | sehr zufrieden (+50)*
Self-perceived thermal control (control)	To what extent are you able to control how warm or cold you feel at this moment? *Wie sehr können Sie im Moment beeinflussen, wie warm oder kalt Sie sich fühlen?*	Not at all (−50) | very much (+50) *gar nicht (−50) | sehr stark (+50)*

[a]Codings were not visible to participants.

lattice[46]) gave a review of the relationships between analysis variables and study conditions per participant. Based on this, different intercepts and slopes for participants and condition were assumed (an exemplary xy plot is presented in the supporting information).

Season was operationalized in the model as running mean outdoor temperature (T_{rm}). The running mean outdoor temperature was calculated using measured hourly outdoor temperatures of the seven days prior to the experimental day and applying the equation given in EN 15251. As such, seasonal influences were covered by variations in observed outdoor temperatures.

Three independent analyses were conducted with the dependent variables overall satisfaction (ov.sat), thermal satisfaction (therm.sat), and visual satisfaction (vis.sat) as measured in the end questionnaire. Independent variables were therm.sat (except for the analysis with therm.sat as dependent variable), vis.sat (except of analysis with vis.sat as dependent variable), self-perceived thermal control (control), indoor illuminance (ill.indoor), outdoor illuminance (ill.outdoor), and calculated values of predicted mean vote (PMV) and the standard effective temperature (SET). PMV and SET values were calculated with the comf package of R[47,48] according to Fanger[49] and Gagge,[50] respectively, on the basis of room parameters and questionnaire data. Note that either PMV or SET was included in the model. The clothing insulation level required for both indices was assessed via questionnaire items and multiplied with corresponding isolation values and then added up to one clothing value (clo) per person.[51] The insulation of the chair (0.1 clo) was added. Metabolic rate was assumed as sedentary (1.2 met).[51] PMV and SET were used as independent variables instead of adding all their input parameters individually in order to reflect the thermal exposure more holistically than just by operative temperature and at the same time to reduce the number of variables in the models. All models were analyzed including PMV or SET, but only models including PMV are presented here, because they consistently had higher R^2 values. Age-group and sex were additional independent variables. Random effects for participant and condition were assumed. According to Gelman,[52] condition is defined as random effect because the conditions selected are a small part of the population of all possible conditions and supposed to vary across individuals. Including condition as random effects enables us to improve our ability to describe how, for example, thermal satisfaction relates to overall satisfaction and permits broader-level inferences about the larger population of participants, which do not depend on a particular condition.

Fixed effects were all independent variables including season (operationalized via T_{rm}), age-group, and sex. The ranges of the dependent and independent variables are different scales, for example, 100 for satisfaction votes (−50 to +50) and several thousand for illuminance. These differences in ranges require normalization of all variables in order to use them in a single model and apply them properly. Therefore, all variables were normalized using function scale() in R, which means that each value was first divided by the standard deviation of the variable in question and then the variable was centered around 0 by subtracting the mean. Outliers were excluded

based on Cook's distance with a cutoff value of $d < 4 \times \text{mean}(d)$.[53] Only models without outliers are reported.

Starting with the null model, the analysis took the following steps:

1. Models with only physical variables included, with and without control as covariate.
2. Models with only questionnaire items regarding thermal and visual satisfaction, with and without control as covariate.
3. Models combining both physical factors and questionnaire items referring to thermal and visual satisfaction, with and without control as covariate.
4. Moderator models, considering PMV and control as moderator.

Tables 4–6 summarize the models analyzed for overall, thermal, and visual satisfaction together with their R notations. Note that model variations related to random intercepts and slopes are based on tests with a larger variety of models and resulting goodness-of-fit criteria.

Restricted maximum-likelihood (REML)[54] estimates for model fit were reported because these estimates are less biased than maximum-likelihood estimates. In addition, the Akaike information criterion (AIC)[55] and Bayesian information criterion (BIC)[56] values are reported to balance between the model complexity (number of independent variables) and goodness of fit.[55,56] Pseudo-R-squared for generalized mixed-effects models (R-package MuMin[57]) was calculated. Marginal R-squared (R^2m) represents the variance explained by the fixed effects, while conditional R-squared (R^2c) is interpreted as the variance explained by the whole model, including fixed and random effects. Values and significance of regression coefficients were examined via R-package lmerTest using Satterthwaite's degrees of freedom method. p-values below $p < 0.05$ were regarded as significant. The models described in detail in section 3.3 were each chosen based on the performance criteria REML, AIC, BIC, and R^2m.

3 | RESULTS

Results are grouped according to the conditions during the experiments, the temperature and light preferences of participants, and the mixed model results for overall, thermal, and visual satisfaction.

3.1 | Conditions during the experiments

In total, 986 participant sessions were conducted. Figure 4 shows means and variance of the physical data per season and condition. Across all six study conditions and the 61 participants, T_{op} ranged from 19.9°C to 36.9°C ($N = 986$ measuring points of the participants, mean = 25.4°C ± 3.1 standard deviations (SD)) and T_{rm} (mean = 11.7°C ± 6.3) from −1°C to 23.3°C. Indoor illuminance at the workplace (ill.indoor) ($N = 890$) varied between 19 lux and 8253 lux (mean = 1100 lux ± 1060) and horizontal outdoor illuminance

TABLE 4 Summary of models and their R notations for overall satisfaction as dependent variable

Model	Model description	R notation[a]
M.ov.sat0	Null model	ov.sat ~1+(1|condition)+(1|participantID)
M.ov.sat.phys	Random intercept and random slope models, intercept and slope separately, assuming no correlations between them, intercept varying among condition and participant within condition for PMV, including self-perceived control	ov.sat ~sex+agegroup+ (1|condition)+ (1|participantID)+PMV+ (0+PMV|condition/ participantID)+ ill.indoor+(0+ill.indoor|conditi on)+Trm+(0+Trm|condition)+ ill.outdoor+ (0+ill. outdoor|condition)+control+ (0+control|condition/ participantID)
M.ov.sat.subj	Random intercept and random slope models, intercept and slope separately, assuming no correlations between them, intercept varying among condition and participant within condition for all items, including self-perceived control	ov.sat ~sex+agegroup+therm.sat+ (0+therm.sat|condition/ participantID)+ vis.sat+ (0+vis.sat|condition/ participantID)+ control+ (0+control|condition/ participantID)+(1|condition)+ (1|participantID)
M.ov.sat.mod1	Moderator model including PMV and self-perceived control	ov.sat ~sex+ agegroup+therm.sat*vis.sat*PMV+therm. sat*vis.sat*control+ (1|condition)+ (1|participantID)
M.ov.sat.physsubj	Random intercept and random slope models, intercept and slope separately, assuming no correlations between them, intercept varying among condition and participant within condition, including self-perceived control	ov.sat ~sex+agegroup+ (1|condition)+(1|participantID)+ PMV+ (0+PMV|condition/participantID)+ ill.indoor+ (0+ill.indoor|condition)+ Trm+(0+Trm|condition)+ ill.outdoor+(0+ill.outdoor|condition)+ therm. sat+ (0+therm.sat|condition/participantID)+ vis. sat+ (0+vis.sat|condition/participantID)+ control+ (0+control|condition/participantID)
M.ov.sat.mod2	Moderator model with questionnaire items and physical variables as predictors, control as moderator	ov.sat ~sex+ agegroup+PMV+ ill.indoor+Trm+ ill. outdoor+therm.sat*vis.sat*control+ (1|condition)+(1|par ticipantID)

Note: [a]Interested readers are referred to introductions to R software and mixed model notations such as Barr et al.[70] Basically, a "+" sign denotes that two variables, but not their interaction, are considered; a "*" sign will include two or more variables and their interactions. The notation (X|Y) determines whether the random factor is modeled for intercepts only (1|random factor), slope only (0+fixed factor|random factor), or both (1+fixed factor|random factor).

TABLE 5 Models and R notations for thermal satisfaction as dependent variable

Model	Model description	R notation
M.therm.sat0	Null model	therm.sat ~1+(1|condition)+(1|participantID)
M.therm.sat.phys	Random intercept and random slope models, intercept and slope separately, assuming no correlations between them, intercept varying among condition and participant within condition for PMV and control	therm.sat ~sex+agegroup+ (1|condition)+ (1|participantID)+PMV+ (0+PMV|condition/ participantID)+ ill.indoor+(0+ill.indoor|conditi on)+Trm+(0+Trm|condition)+ ill.outdoor+ (0+ill. outdoor|condition)+control+ (0+control|condition/ participantID)
M.therm.sat.subj	Random intercept and random slope models, intercept and slope separately, assuming no correlations between them, intercept varying among condition and participant within condition for all items, including control	therm.sat ~sex+agegroup+vis.sat+ (0+visssat|condition/ participantID)+ control+ (0+control|condition/ participantID)+(1|condition)+ (1|participantID)
M.therm.sat.mod1	Moderator model including visual satisfaction and self-perceived control	therm.sat ~sex+ agegroup+vis.sat*control+ (1|condition)+ (1|participantID)
M.therm.sat.physsubj	Random intercept and random slope models, intercept and slope separately, assuming no correlations between them, intercept varying among condition and participant within condition, including self-perceived control	therm.sat ~sex+agegroup+ (1|condition)+(1|participantID) +PMV+ (0+PMV|condition/participantID)+ ill.indoor+ (0+ill.indoor|condition)+ Trm+(0+Trm|condition)+ ill.outdoor+(0+ill.outdoor|condition)+ vis.sat+ (0+vis.sat|condition/participantID)+ control+ (0+control|condition/participantID)
M.therm.sat.mod2	Moderator model with age, sex, and physical variables as predictors, control as moderator	therm.sat ~sex+ agegroup+PMV+ ill.indoor+Trm+ ill. outdoor+vis.sat*control+ (1|condition)+(1|participantID)

TABLE 6 Models and R notations for visual satisfaction as dependent variable

Model	Model description	R notation
M.vis.sat0	Null model	vis.sat ~1+(1|condition)+(1|participantID)
M.vis.sat.phys	Random intercept and random slope models, intercept and slope separately, assuming no correlations between them, intercept varying among condition and participant within condition for PMV	vis.sat ~sex+agegroup+ (1|condition)+ (1|participantID)+PMV+ (0+PMV|condition/participantID)+ ill.indoor+(0+ill.indoor|condition)+Trm+(0+Trm|condition)+ ill.outdoor+ (0+ill.outdoor|condition)
M.vis.sat.subj	Random intercept and random slope models, intercept and slope separately, assuming no correlations between them, intercept varying among condition and participant within condition for all items, including control	vis.sat ~sex+agegroup+therm.sat+ (0+therm.sat|condition/participantID)+ control+ (0+control|condition/participantID)+(1|condition)+ (1|participantID)
M.vis.sat.mod1	Moderator model including visual satisfaction and self-perceived control	vis.sat ~sex+ agegroup+therm.sat*control+ (1|condition)+ (1|participantID)
M.vis.sat.physsubj	Random intercept and random slope models, intercept and slope separately, assuming no correlations between them, intercept varying among condition and participant within condition, including self-perceived control	vis.sat ~sex+agegroup+ (1|condition)+(1|participantID)+ PMV+ (0+PMV|condition/participantID)+ ill.indoor+ (0+ill.indoor|condition)+ Trm+(0+Trm|condition)+ ill.outdoor+(0+ill.outdoor|condition)+ therm.sat+ (0+therm.sat|condition/participantID)+ control+ (0+control|condition/participantID)
M.vis.sat.mod2	Moderator model with sex, age, and physical variables as predictors, control as moderator	vis.sat ~sex+ agegroup+PMV+ ill.indoor+Trm+ ill.outdoor+therm.sat*control+ (1|condition)+(1|participantID)

(ill.outdoor) (N = 911) from 982 to 100 000 lux (mean = 59 400 lux ± 36 690). Further descriptive statistics of the physical data is available in the supporting information.

In relation to the intended conditions, mean values of T_{op}, PMV, and SET differed following the experimental design in T conditions across all seasons, while they were comparable among the L conditions. Indoor illuminance varied largely among seasons during the T conditions. During the L conditions, indoor illuminance varied according to the experimental protocol, that is, at three distinct levels between L1 and L3, though deviations from intended conditions are larger (see also Discussion section).

3.2 | Temperature and light preferences of participants

The questionnaire ratings for overall, thermal, and visual satisfaction along with self-perceived thermal control are summarized in Table 7 and Figure 5. Disregarding individual conditions, as observable in Table 7, mean ratings for visual satisfaction were on average the highest followed by overall satisfaction. At the same time, overall satisfaction had the least variance followed by visual satisfaction. Mean outcome of overall satisfaction was 19.86 (SD: 21.86) on the scale from −50 to +50 indicating a moderate-to-high overall satisfaction with indoor environmental conditions.

When considering individual conditions and seasonal differences (Figure 5), the following observations can be made. Note that interpretation needs to be done cautiously as the number of participants varies among combinations of condition and season.

Still, some general trends can be observed and will be reflected based on results of the mixed-effects model analysis: Highest mean values of overall satisfaction were reached in condition T2 in all seasons, with operative temperatures around 25°C and modifiable visual stimuli. In L conditions, means of overall satisfaction vary with season, with summer season leading to highest values except for L2 condition.

Ratings for overall and thermal satisfaction were higher in L conditions and T2 compared with conditions T1 and T3.

Ratings for visual satisfaction were higher in T conditions than in L conditions, that is, visual satisfaction was higher when participants were able to control visual conditions.

As expected, mean values of perceived thermal control were higher in visual conditions, when participants had larger control over thermal exposures, than in thermal conditions. The highest mean values of control in the thermal conditions were reached in T2. Interestingly, mean values of perceived thermal control in L conditions varied systematically in the different seasons with summer season being related to highest perceived thermal control and vice versa with winter season.

3.3 | Crossed and combined effects on overall, thermal, and visual satisfaction

In the following, for each independent variable analyzed, that is, overall, thermal, and visual satisfaction, first, the analyzed models' performances are presented followed by a more detailed description of one of the tested model, selected based on goodness-of-fit parameters.
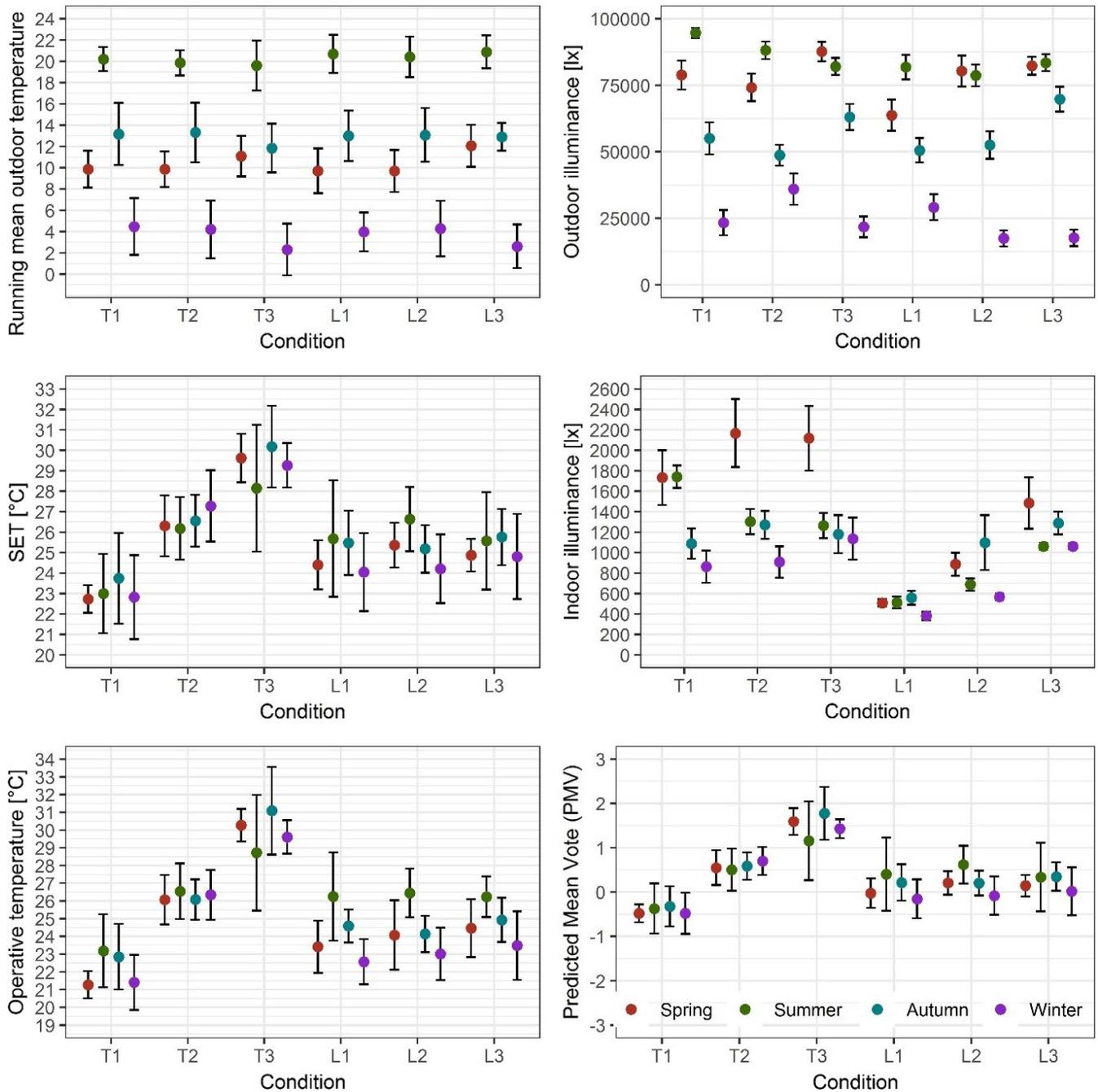
FIGURE 4 Means and standard deviations/errors of physical data in the last 5 min before filling in the end questionnaire (per season and condition, *N* = 61 participants, individual *N* varies with number of participants). Note: For outdoor and indoor illuminance, standard errors are shown

3.3.1 | Overall satisfaction (ov.sat)

Random intercept and slope models for overall satisfaction as dependent variable with only physical variables explained up to 15% of variance, while those models including only subjective ratings of "thermal satisfaction," "visual satisfaction," and "control" explained up to 61% of variance. Random intercept and slope models including subjective ratings of control, thermal, and visual satisfaction and physical variables explained up to 81% of variance of the whole

model and up to 55% of the variance of the fixed effects. Moderator models (including control and/or PMV as moderator) explained up to 63% of variance. Details for the mixed models with overall satisfaction as dependent variable are described in the supporting information.

In the random intercept and slope models (M.ov.sat.phys, M.ov.sat.subj, and M.ov.sat.physsubj), the highest amount of variance (disregarding residual variance which values lied between 46.7% and 76.6%) explained by random effects is found—across all models—for

TABLE 7 Descriptives of analyzed (questionnaire) variables (across all study conditions, N = 61 participants)

	Overall satisfaction	Thermal satisfaction	Visual satisfaction	Self-perceived control
N	892	889	891	892
Mean	19.86	8.92	21.26	0.82
Standard deviation	21.86	31.03	24.33	30.69
Percentiles				
1	−41.00	−50.00	−41.00	−50.00
25	9.00	−17.00	9.00	−28.00
50	24.00	15.00	28.00	10.00
75	37.00	37.00	41.00	26.00
99	50.00	50.00	50.00	50.00

participant (10.3%-26.6%). Condition explained only 0.003% to 1.4% of variance across all models. Different values were found in the moderator models (M.ov.sat.mod1, M.ov.sat.mod2): Participant accounted for 5.8–16.2% of variance (residual variance: 78.5% to 84.9%), and up to 5.3% of variance was accounted by condition. There were no significant fixed effects for the models including only physical measures of indoor and outdoor temperature and illuminance (M.ov.sat.phys), even if control as covariate is added (see supporting information). While the lowest AIC and BIC are for the random intercept and slope model (M.ov.sat.physsubj), none of the physical variables included in this model, that is, PMV, indoor illuminance, outdoor illuminance, and T_{rm}, were significant. With the highest R^2m for the moderator model (M.ov.sat.mod1), this model will be presented and discussed below.

Based on the moderator model (M.ov.sat.mod1), thermal satisfaction and visual satisfaction were the most important predictors for overall satisfaction (see Table 8). Thermal satisfaction had more influence (0.57) on overall satisfaction than visual satisfaction (0.34). An increase in control corresponds to a slight increase in overall satisfaction (0.09). T_{rm} had a tendency to influence on overall satisfaction vote (0.04), but the value was lower than for perceived control. There was a significant moderation effect of control on the relationship between thermal and overall satisfaction but not for visual and overall satisfaction. The moderator models suggest that:

- the effect of thermal satisfaction on overall satisfaction was different for different values of control (interaction term therm. sat: control = −0.12) indicating that by increasing control, the effect of thermal on overall satisfaction decreased or in other words control slightly reduced the effect of thermal on overall satisfaction (control as moderator as visualized in Figure 6).
- the influence of thermal on overall satisfaction was higher (0.54) than the effect of visual on overall satisfaction (0.37).

Other interactions between control, thermal, and visual satisfaction were nonsignificant, and the same applies to sex, age-group, and T_{rm}.

Figure 7 presents the predicted overall satisfaction by season (low/high T_{rm}) and perceived level of thermal control (low/high). In general, self-perceived thermal control increased overall satisfaction, and only in case both thermal and visual satisfaction are high, and overall satisfaction is high as well.

3.3.2 | Thermal satisfaction (therm.sat)

Analyzing thermal satisfaction as dependent variable revealed that in the model with only physical variables as predictors (M.therm. sat.phys) outdoor illuminance and the calculated PMV based on measured physical parameters were significant and including self-perceived thermal control explained variance increased up to 66%. Details for the mixed models with thermal satisfaction as dependent variable are described in the supporting information.

In the following, the moderator model with the highest R^2m value (M.therm.sat.mod2) is described in detail. Table 9 presents estimates for this moderator model including physical parameters, visual satisfaction, and self-perceived control. Significant variables are PMV, visual satisfaction, and self-perceived thermal control, but not the interaction between visual satisfaction and self-perceived control. The models' behavior is visualized in Figure 8, which shows clear differences with and without control on thermal satisfaction, highlighting the main effect of control (0.55).

3.3.3 | Visual satisfaction (vis.sat)

Variance explained by the fixed effects in the models with visual satisfaction as dependent variable is in general extremely low, that is, R^2m values below 0.1 (see supporting information). Considering fixed and random effects, random intercept models with physical variables explained 36% of variance in visual satisfaction, revealing no significant fixed effect. As expected, self-perceived thermal control was not a significant predictor for visual satisfaction in any of the models. Details for the mixed models with visual
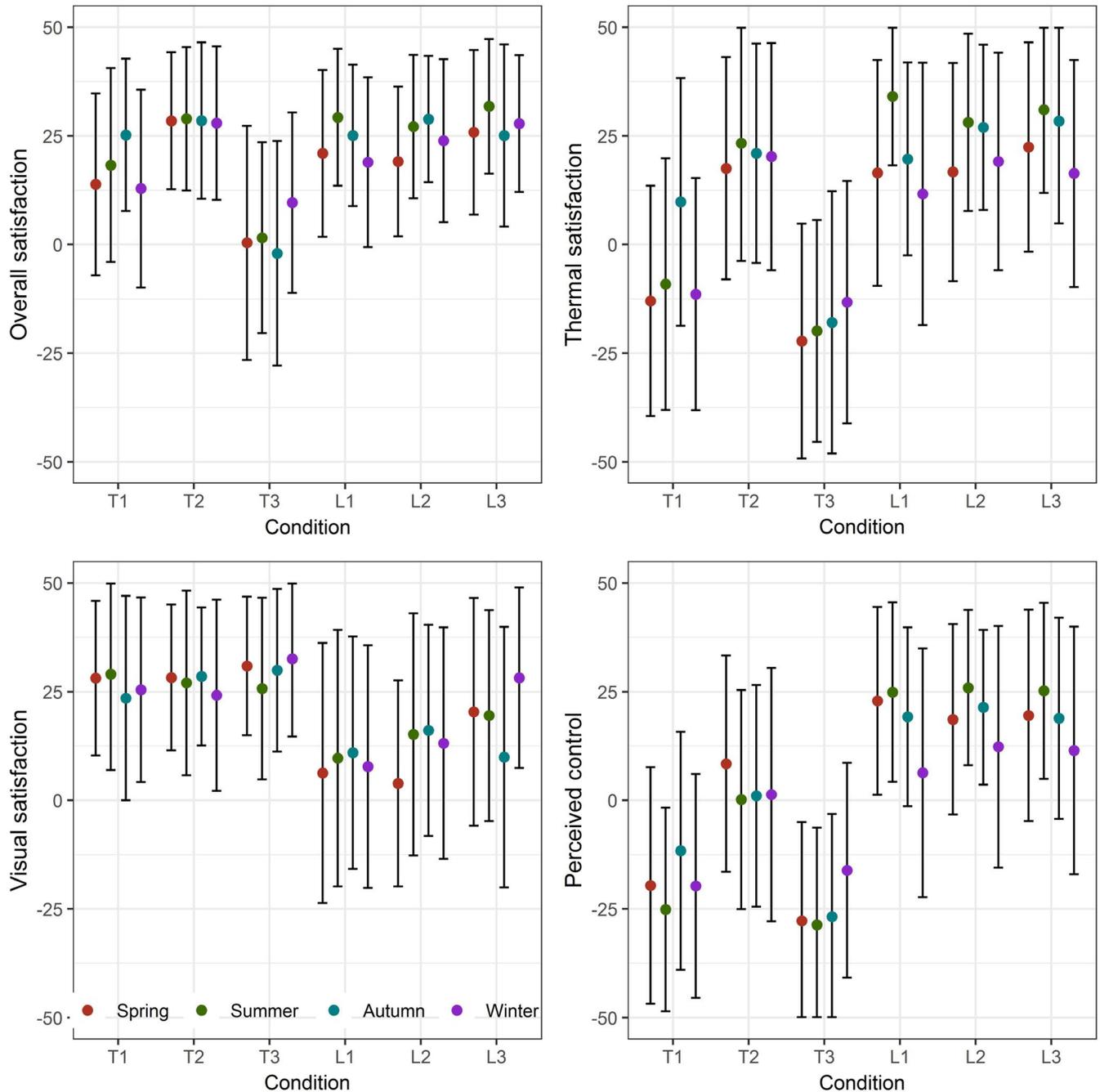
FIGURE 5 Means and standard deviations of analyzed (questionnaire) variables (per season and condition, N = 61 participants): (A) overall satisfaction, (B) thermal satisfaction, (C) visual satisfaction, and (D) perceived thermal control. T1, T2, and T3 (fixed temperature at 20°C, 25°C, and 30°C), L1, L2, and L3 (fixed illuminance around 300 lux, 500 lux, and 1000 lux, respectively)

satisfaction as dependent variable are described in the supporting information.

For detailed presentation, the moderator model (M.vis.sat.mod2) with lowest AIC and BIC was chosen.

Estimates for the fixed effects of this moderator model predicting visual satisfaction are presented in Table 10. Only thermal satisfaction has a significant effect, with PMV showing a tendency. Variables expected to affect visual satisfaction significantly, indoor and outdoor illuminance, returned nonsignificant. The models' behavior is visualized in Figure 9, demonstrating

the small effect even of these two main variables on visual satisfaction.

4 | DISCUSSION

In this study, we tested the hypothetical model presented in Figure 1 through a carefully designed experimental study. This discussion will first focus on thematic considerations and later on the methodological aspects.

TABLE 8 Estimates of the fixed effects for the moderator model (M.ov. sat.mod1) with overall satisfaction as dependent variable and thermal and visual satisfaction as independent variable, and moderator as control. Note that T_{rm}, thermal and visual satisfaction, and control were standardized according to their mean and variance. Model parameters are $R^2m = 0.61$ and $R^2c = 0.71$

Variable	Estimate	Standard error	df	t value	Pr(>|t|)
(Intercept)	0.18	0.10	24.3	1.74	0.09
Sex (female)	−0.05	0.09	42.0	−0.61	0.54
Age-group (young)	−0.13	0.09	42.03	−1.50	0.14
Trm	0.04	0.02	674.09	1.69	0.09
Thermal satisfaction (therm.sat)	0.57	0.03	670.74	17.15	<0.001***
Visual satisfaction (vis. sat)	0.34	0.03	674.61	10.18	<0.001***
Perceived control (control)	0.09	0.03	638.27	2.72	0.01*
Therm.sat: vis.sat	0.05	0.03	667.59	1.45	0.15
Therm.sat: control	−0.12	0.03	677.74	−4.60	<0.001***
Vis.sat: control	0.03	0.03	662.43	−0.94	0.35
Therm.sat: vis.sat: control	−0.02	0.03	651.65	−0.81	0.42

Significance codes: "****"<0.001, "**"<0.01, "*" <0.05.

FIGURE 6 Three-way interaction between thermal satisfaction, visual satisfaction, and control on overall satisfaction (model M.ov.sat.mod1)
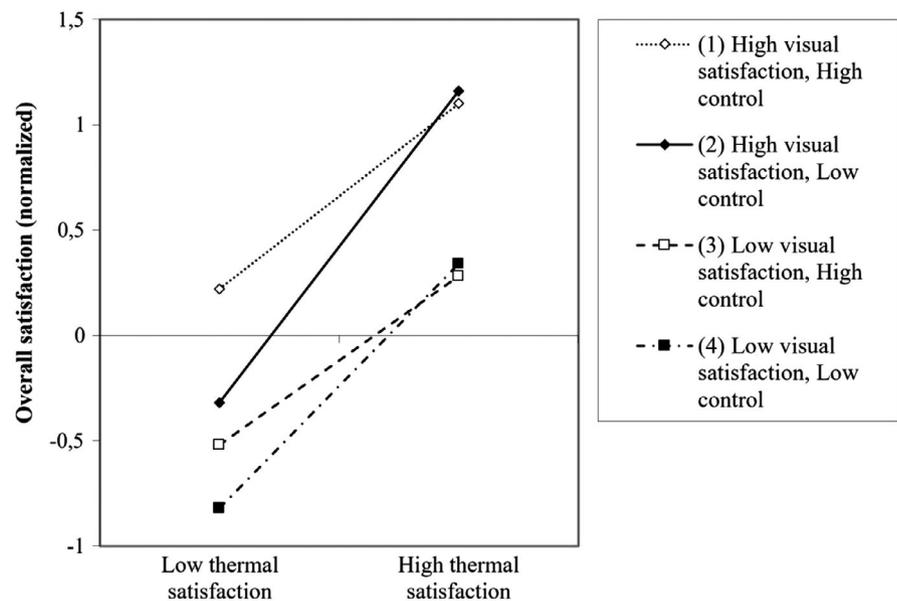
4.1 | Thematic considerations

This section discusses results obtained for the analysis of interactions on overall satisfaction, combined effects on thermal satisfaction, and visual satisfaction. In each section, results from the mixed models will be discussed alongside observations from the descriptive analysis. As mentioned in the introduction, authors are not aware of other studies analyzing interactions between thermal and visual aspects under varying control scenarios so that direct comparisons to existing studies need to be done carefully.

The major findings to be discussed are:

1. self-perceived control moderates the interaction between thermal and visual conditions on overall satisfaction and influences thermal satisfaction.

2. overall satisfaction and visual satisfaction are strongly affected by subjective ratings rather than physical parameters.

3. thermal and visual satisfaction are the most important predictors for overall satisfaction with thermal satisfaction having a stronger influence, but their interaction being not significant. Crossed effects were observed for thermal satisfaction on visual satisfaction and for visual satisfaction on thermal satisfaction.

In the present study, perceived thermal control reduced the effect of thermal satisfaction on overall satisfaction suggesting control being an important moderator of the influence of thermal satisfaction on overall satisfaction. Once people have control over the thermal environment, dissatisfaction with the thermal environment less affects overall satisfaction. Also, according to mean values presented in Figure 5, perceived control was highest
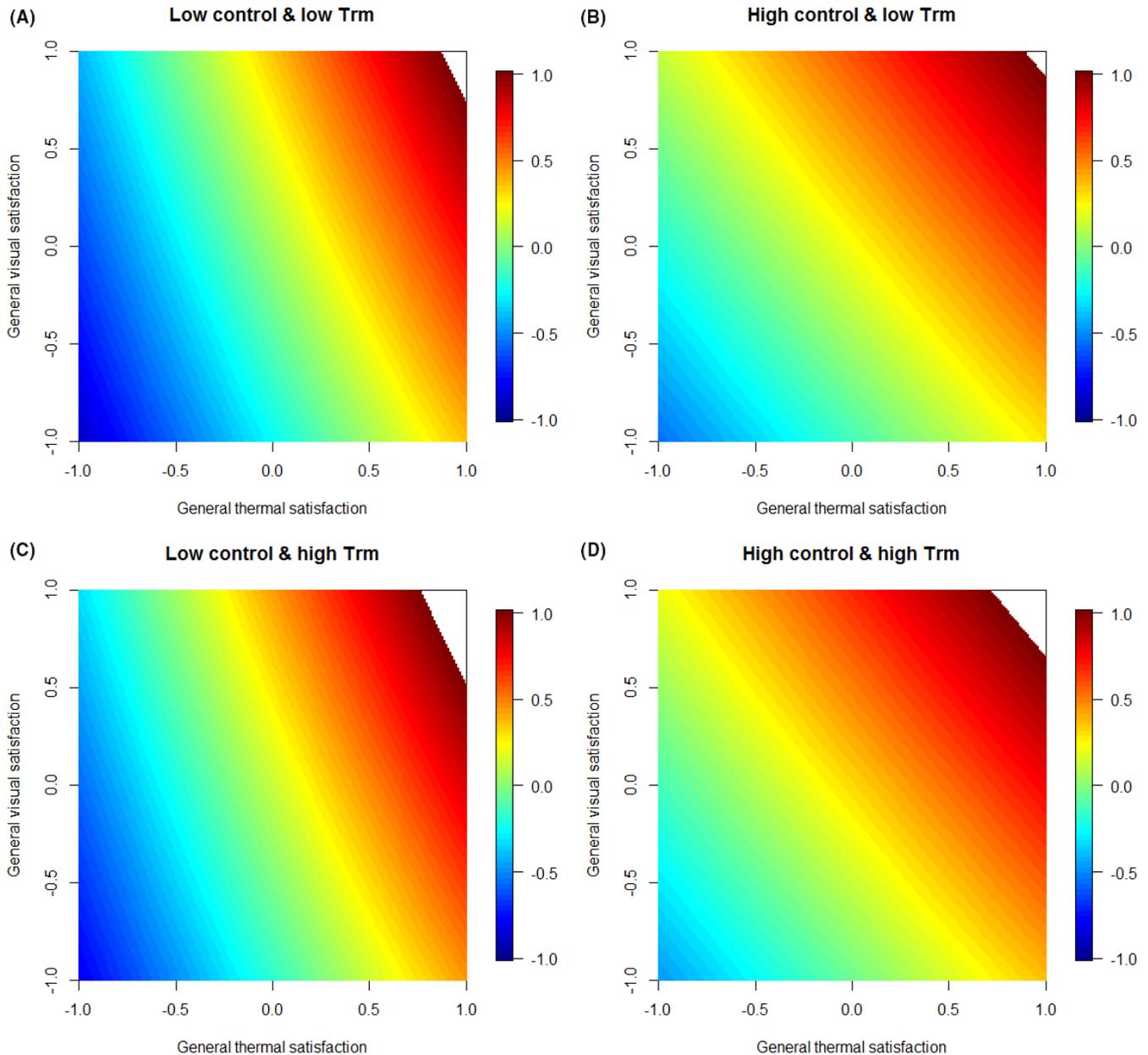
(A)

Low control & low Trm

(B)

High control & low Trm

(C)

Low control & high Trm

(D)

High control & high Trm

FIGURE 7 Predicted overall satisfaction according to observed thermal satisfaction, visual satisfaction, self-perceived control, and season. Note that variables were scaled, that is, a value of 1.0 in overall satisfaction corresponds to a value of +50 on the visual analogue scale. Low T_{rm} refers to a scaled value of −1, that is, 5.4°C before scaling, and high T_{rm} refers to +1, that is, 18°C. Low control refers to −1, that is, a value of −30 on the visual analogue scale, and high control refers to +1, that is, +31.5

at T2 conditions (25°C) compared with T1 (20°C) and T3 (30°C). Our hypothesis with this respect is that T2 conditions (25°C) are closer to thermal neutrality and therefore participants might have perceived more control opportunities of their individual thermal exposures by means of clothing level adjustments, while such measure had limitations at T1 (20°C) and T3 (30°C). The effect of perceived thermal control on thermal satisfaction is in line with previous single-domain studies on this topic.[19-21] At the same time, results are not comparable to multidomain studies, because the study by Pellerin and Candas mentioned introductory investigated interactions between thermal and acoustic stimuli and

control was given to their participants to improve one domain, while the other worsened.[31]

While results suggest evidence for control as moderator, several limitations have to be mentioned here. First, perceived thermal control was measured as a single-item self-perceived control question related to the thermal environment. There are evidences that one could obtain other results when, for example, using self-efficacy scales rather than one item measures of perceived control. For example, Hawighorst et al[58] found significant influences of self-efficacy on overall satisfaction/comfort. In addition, future studies should add self-perceived control of visual environment to

TABLE 9 Estimates of the fixed effects for the moderator model (M.therm. sat.mod2) with thermal satisfaction as dependent variable and visual satisfaction, calculated PMV, illuminance indoors and outdoors, and season as independent variable, and moderator as control. Note that all continuous variables were scaled. Model parameters are $R^2m = 0.38$ and $R^2c = 0.54$

| Fixed effects	Estimate	Standard error	df	t value	Pr(>|t|)
Intercept	0.06	0.12	16.57	0.50	0.62
Sex (female)	−0.01	0.11	43.6	−0.11	0.91
Age-group (young)	0.17	0.11	43.74	0.16	0.88
PMV (poly1)	0.01	0.05	152.77	0.34	0.73
PMV (poly2)	−0.09	0.02	515.09	−3.57	<0.001***
Indoor illuminance	−0.02	0.03	538.91	−0.57	0.57
Trm	0.04	0.03	550.99	1.07	0.29
Outdoor illuminance	0.07	0.04	545.77	1.95	0.05
Visual satisfaction (vis.sat)	0.10	0.04	532.21	2.88	0.004**
Perceived control (control)	0.55	0.04	393.53	13.52	<0.001***
Vis.sat: control	−0.05	0.03	538.98	−1.53	0.13
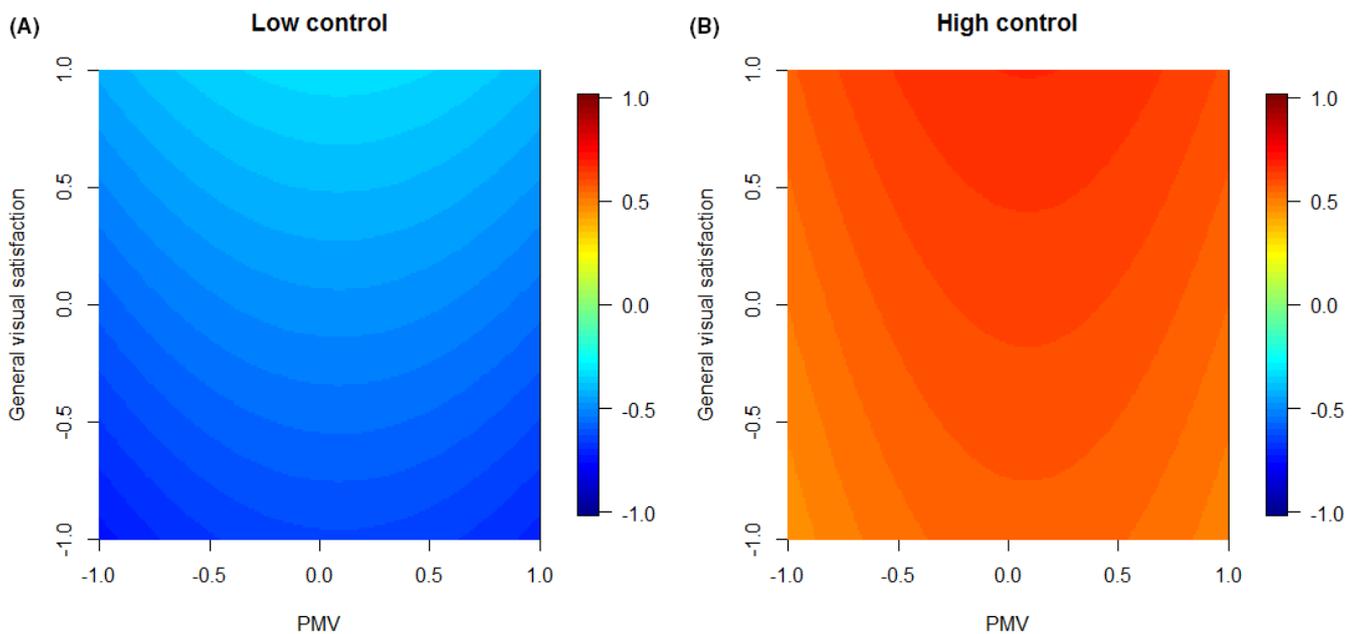
FIGURE 8 Predicted thermal satisfaction according to observed PMV, visual satisfaction, and self-perceived control. Note that variables were scaled, that is, a value of 1.0 in thermal satisfaction corresponds to a value of +50 on the visual analogue scale and a value of −1 of PMV corresponds to an observed value of −3. Low control refers to −1, that is, a value of −30 on the visual analogue scale, and high control refers to +1, that is, +31.5

enable the assessment of its effect on visual satisfaction or as moderator to the influence of visual satisfaction on overall satisfaction. Second, previous studies have shown that perceived control is lower in a two-person office compared with a single-person office.[25] This study was conducted in two-person offices, but did not permit assessing the effect of the other person in the same room on the level of perceived control. Therefore, part of the variance in perceived thermal control may be due to differences in the way participants' perceived thermal control was affected by the other person and not by the experimental conditions.

At the same time, season—represented in this study through T_{rm}—was not significant on either of the three dependent variables analyzed despite a large body of literature showing seasonal effects

on thermal and visual perception.[34,59] Two arguments can be found for these findings. First, despite operable windows to the exterior this study were conducted in a laboratory environment, which might have reduced one or more of the three mechanisms leading to seasonal adaptation, namely physiological, behavioral, and psychological adaptation. In particular, participants may have physiological adapted to distinct conditions. Despite living in the same climatic region as the LOBSTER, differences in building envelope and technical systems of buildings inhabited for work and home may lead to some participants experiencing stable and others higher seasonal fluctuations in thermal and visual conditions. Such differences likely reduce systematic physiological adaptive processes. Furthermore, aspects related to psychological adaptation such as habit and expectation

Fixed effects	Estimate	Standard error	df	t value	Pr(>|t|)
Intercept	−0.05	0.19	17.17	−0.25	0.80
Sex (female)	−0.04	0.16	46.41	−0.25	0.80
Age-group (young)	−0.06	0.16	46.66	−0.38	0.71
PMV (poly1)	−0.1	0.06	256.5	−1.66	0.098
PMV (poly2)	0.05	0.03	536.15	1.63	0.10
Indoor illuminance	0.01	0.03	527.68	0.37	0.71
Trm	−0.05	0.04	542.23	−1.08	0.28
Outdoor illuminance	−0.04	0.05	535.39	−0.79	0.43
Thermal satisfaction (therm.sat)	0.11	0.05	550.3	2.08	0.04*
Perceived control (control)	−0.09	0.05	526.27	−1.6	0.11
Therm.sat: control	0.07	0.04	545.81	1.79	0.07

TABLE 10 Estimates of the fixed effects for the moderator model (M.vis. sat.mod2) with visual satisfaction as dependent variable and physical variables and thermal satisfaction as independent variable, and moderator as control. Note that T_{rm}, thermal and visual satisfaction, and control were scaled. Model parameters are $R^2 m = 0.02$ and $R^2 c = 0.36$
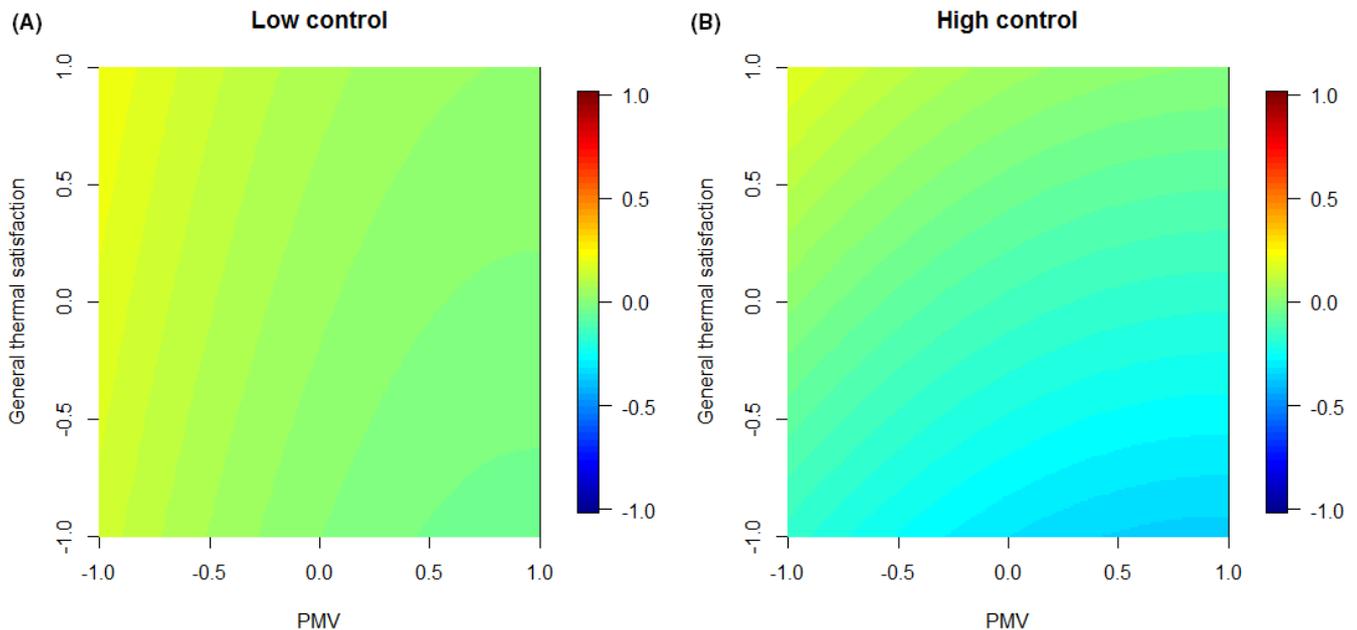

FIGURE 9 Predicted visual satisfaction according to observed PMV, thermal satisfaction, and self-perceived control. Note that variables were scaled, that is, a value of 1.0 in visual satisfaction corresponds to a value of +50 on the visual analogue scale and a value of −1 of PMV corresponds to an observed value of −3. Low control refers to −1, that is, a value of −30 on the visual analogue scale, and high control refers to +1, that is, +31.5

might be reduced in this environment. Despite previous studies in the same laboratory demonstrating that adaptive processes are occurring and measurable in this context,[60] this effect might have been reduced to non-significance in the multidomain context of this study. Second, seasonal influences on interactions might be more complex and less linear as analyzed in this study. As demonstrated by Moosmann,[34] seasonal effects on preferred illuminance levels are not linear, so that the approach used here, based on T_{rm}, might not be appropriate. Future analyses and studies need to assess whether other operationalization of season leads to other results. As observed in Figure 5, mean values of perceived thermal control in L conditions varied with summer season being related to highest and

winter season with lowest perceived thermal control. These results would be worth further explorations in future studies. On the one hand, such observation is in line with observations related to the adaptive thermal comfort approach,[21,59] which suggests that participants are adapted to warmer conditions and hence have a lower demand for controlling thermal conditions. On the other hand, this observation is in contrast to the conclusions by Boerstra et al[19] that perceived control correlates with the effectiveness of control. In summer season, opening a window has a smaller cooling potential, than in winter. Hence, effectiveness of opening windows for thermal control is higher in winter, which contradicts our findings of higher perceived control in summer.

A *second* important finding of this study is the difference between the importance of objective and subjective independent variables. Models including subjective ratings of thermal and/or visual satisfaction with room conditions explain more variance than models with only physical variables. Such result suggests that subjective perception of thermal or visual comfort is more important than the physical room conditions such as temperature or illuminance. Within this context, especially visual satisfaction in the illuminance range considered in this study (approx. 300 lx–1000 lx horizontal at workplace in L conditions, approx. 700–2500 lx in T conditions) appears to vary largely between individuals, or with variables not assessed here. It has to be mentioned that the illuminance levels L1, L2, and L3 are appropriate for office workplace and that (higher) illuminance levels in T conditions have been controlled by the users, so that visual stimuli are not as extreme as thermal stimuli. On the one hand, this result showing a strong subjective element in the evaluation supports previous research showing rather weak relationships between objective IEQ conditions and subjective votes.[61] The weakness of this relationship may have been further increased by applying a visual analogue scale (VAS) rather than a 7-point scale applied in many studies. The visual analogue scale may increase the variance due to different response styles of participants with some preferring using extremes and others having a tendency to the middle, so that this observation is likely affected by an increased correlation between self-assessed satisfactions also known as a common methods bias.[62] A VAS was applied here, because of its advantages over categorical scales in terms of data type obtained (continuous, rather than ordinal). In addition, typically applied scales to assess thermal satisfaction, visual satisfaction, and perceived control are based on distinct numbers of response categories ranging between 5 and 7. Future analysis will need to assess these potential uncertainties in the results introduced through the choice of a VAS. In addition, interindividual differences might have been increased by the type of work performed by the participants. While participants were free to choose the type of work, some worked on their computer, while others engaged in reading tasks. This natural setting added further uncontrolled variance to the data. The introduced random-effects term likely captured parts of interindividual differences with this respect, but is not able to capture intraindividual day-to-day differences in the type of work performed. Such aspects need to be further controlled or at least monitored in future studies in order to quantify the corresponding effect and its influence on the results presented here.

Within this context, it is also worth discussing are the large intraindividual differences in ratings. The relatively high amount of residual variance in some of the models in the present study suggested that there were intraindividual differences in ratings of thermal, visual, or overall satisfaction. A first look into our data suggested that there are individuals who made different ratings on thermal comfort scales even if they experience the same condition in the same season. Adaptation and data analysis by means of reliable change index (RCI)[63] from psychotherapy research could provide information about such intraindividual changes in the assessments of thermal comfort. In addition, the large intraindividual

differences suggest other potential influencing factors on the dependent variables such as health conditions, actual well-being, self-efficacy, activity level, or—suggested by Keeling et al[64]—appraisal. Furthermore, there is some evidence that physiological thermo-regulation processes influence ratings on thermal and/or visual comfort[32]; Candas and Dufour[65] stated that vasodilation under high-illuminance or high-temperature color environments may slightly lower core temperature, which may act on thermal comfort. The same holds true for influence of medication on thermoregulation,[66,67] which, to the best of our knowledge, has not yet been investigated in the context of comfort research. These factors were not assessed within the present study but could be taken into account when designing future studies on the topic. Yet, it is relatively unknown how thermal and visual parameters interact, especially when taking time or physiological parameters into account.[32] Further studies are needed.

Related to the third main findings on interactions and crossed main effects, our findings are partially in line with previous findings. In line with Chinazzo et al,[14] a crossed effect of visual aspects on thermal response was observed also in this study. However, Chinazzo et al observed an effect of actual illuminance conditions on thermal comfort, while we could not find a significant effect of observed illuminance conditions, but only an effect of self-assessed visual satisfaction on thermal satisfaction. Due to the differences in metrics and levels of illuminance and thermal conditions, a direct comparison remains challenging and underlying reasons can only be speculated on. While being significant, the magnitude of observed effects by Chinazzo et al appears rather small, that is, within the same category of thermal comfort vote. The application of a thermal satisfaction-VAS without intermittent verbal anchors in this study likely further diluted any potential effect of objective visual conditions on thermal responses.

4.2 | Methodological considerations

The experimental design applied aims at a combination of elements found in less-controlled field studies and highly controlled laboratory studies as did earlier studies by the authors (see, eg, [25]). Such combination is associated with advantages and disadvantages as argued in the following. Observational field studies are praised for their high external validity, while having limited potential to reveal cause–effect relationships. On the other hand, experimental studies lack external validity, while enabling cause–effect relationships. In order to combine both methods, one approach may be field studies augmented by experimental elements such as distinct experimentally induced variations in conditions. A challenge in this approach is in the availability of opportunities to apply such studies, because this would require taking over thermal and visual control conditions in real existing buildings, which likely affects participants' satisfaction and performance. At the same time, such approach either requires a large number of such buildings in order to overcome the notion of a case study and still causes

artificial elements reducing external validity, because participants are suddenly exposed by a different—unnatural—behavior of their building. In addition, it would be a challenge to restrict certain controls, which participants were used to in the past, in real buildings without dramatically altering their perceived level of control. The other approach attempts to increase the external validity in highly controlled laboratory studies, while keeping experimental control to a large extend. Such approach is suggested and implemented by the authors of this study. This approach consists of predefined control scenarios and starting conditions with respect to thermal and visual characteristics. At the same time, participants' interactions with the laboratory environment lead to actual changes in the physical (thermal and visual) environment. As such, this approach will lead to a higher variety of actual physical conditions, hence a wider range of perceptions and corresponding responses. At the same time, the authors see this as a strength of the design and not as a pitfall. On the one hand, due to this larger variance in conditions and responses, classical analysis methods such as ANOVA, strictly comparing obtained subjective votes between designed conditions, are not applicable. However, advanced statistical approaches such as multivariable mixed-effects models as applied here, which include the variance in independent variables (either the variance in physical conditions or the variance in perception in case perception is applied as independent variable), are capable of dealing with such variety in underlying experimental conditions as present in this study and still extract the information on cause–effect relationship implied by an experimental setting as we did. Introducing a sort of placebo control, just giving participants the impression that they can adjust physical stimuli would not have the same effect for the following reasons. First, earlier research by the authors has shown that placebo controls are not leading to a higher satisfaction due to missing perceivable effects of the interaction with the control on environmental conditions.[35] In contrast, even reverse effects can be anticipated once participants realize the lack of actual control. As outlined by Boerstra,[68] a high satisfaction with control opportunities requires not only the mere availability of controls, but also a notable effect of ones' actions. Second, this sort of placebo might work for a limited period of time for thermal aspects as at least in areas characterized by water-based heating systems such as Germany, people are used to a time delay between their action of changing a set point and the actual change in perception. However, for visual aspects, such as pressing a light switch or lowering blinds, people are used to instant changes in the visual characteristics. The authors cannot imagine a suitable method to "fake" such control opportunities without actual changes in conditions.

4.3 | Limitations

Additional limitations and related tasks for future studies are as follows. The results are based on data from a laboratory study and should be validated in field studies, for example, real-world office buildings in all seasons. The present data were analyzed using mixed models instead of multilevel modeling (eg, lavaan package in R[69]). Some of the models analyzed, but not presented here, did not converge because of the small sample size. Further research should replicate the results with bigger sample sizes and by analyzing data with, for example, multilevel modeling. The physical variables for thermal and visual environment controlled in this study were operative temperature and illuminance level, respectively. Other environmental variables related to thermal and visual environments such as humidity and correlated color temperature of the lighting could not be controlled, but were measured. However, they could not be included in the analysis at this stage due to the relationship between complexity of the model and available sample size. A larger sample size will be required to include these factors in future studies.

5 | CONCLUSIONS

To date, little information is available on the modeling of relationships between thermal and visual comforts with overall satisfaction when taking into account confounding factors such as season, age, sex, or self-perceived control. The present study is according to our knowledge the first study examining the interactions of thermal and visual conditions in semi-standardized laboratory experiments in all of the four seasons including variations in the level of control. This study thereby contributes considerable results to the discussion on multidomain interactions (see results and discussion section):

- The major finding is a significant moderator effect of self-perceived control on the effect of thermal satisfaction on overall satisfaction. Hence, future studies looking at overall satisfaction need to consider the level of self-perceived control either by assessing and including it into the analysis or by systematically manipulating it.
- Physical variables had low influence on overall satisfaction and visual satisfaction, with all variables being nonsignificant. Only for thermal satisfaction, physical thermal conditions explained parts of the variance and were statistically significant. For thermal satisfaction, self-perceived control had the largest effect, followed by the physical conditions, showing a cross-model interaction between thermal satisfaction and visual satisfaction.
- Physical environmental conditions did not have a significant effect on overall and visual satisfaction likely due to the ranges of conditions applied and the measurement instruments applied.

In conclusion, this study highlights interactions and cross-modal effects between overall, thermal, and visual satisfaction and the important role of self-perceived control. As such, we recommend to carefully assess thermal, visual, and control scenarios jointly and not independently in future research studies and for future building design and operation strategies. Based on this, improvements in the design of the indoor environment can be made, for example, dynamic lighting adjusted to thermal conditions or vice versa to contribute to energy savings.

NOMENCLATURE

T_{rm}	Running mean outdoor temperature
T_{op}	Operative temperature
ov.sat	Overall satisfaction
therm.sat	Thermal satisfaction
vis.sat	Visual satisfaction
Control	Self-perceived thermal control
ill.indoor	Indoor illuminance
ill.outdoor	Outdoor illuminance on the roof
PMV	Predicted mean vote
SET	Standard effective temperature

CONFLICT OF INTEREST

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or nonfinancial interest (such as personal or professional relationships, affiliations, knowledge, or beliefs) in the subject matter or materials discussed in this manuscript.

AUTHOR CONTRIBUTION

All authors revised the manuscript and agreed with its submission. S.L. participated in data analysis and writing of the manuscript. M.S. participated in funding acquisition, design of the experiment, data collection, and analysis and writing of the manuscript. C.M. participated in funding acquisition, design of the experiment, data collection, and writing of the manuscript. A.W. participated in funding acquisition, design of the experiment, and writing of the manuscript.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.