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Effects of personal control for thermal comfort in long-distance trains

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Abstract

As a result of its low environmental impact the railway system is the prime candidate to enable domestic and continental mass passenger mobility. One important aspect determining the attractiveness of rail journeys is the thermal comfort that is provided in a passenger rail car. Newer approaches focusing on the improvement of thermal comfort in passenger rail cars are based on the idea to employ personalized comfort zones. It is generally assumed that individual control over indoor climate settings contributes to the passengers' thermal comfort. The studies presented here further examine this assumption by considering the concept "thermo-specific self-efficacy" (specSE) as psychological construct in the context of thermal comfort in a railway car. Two studies with 11 human subject test runs including 172 subjects in total were performed in a mock-up of a passenger rail car. Environmental climate conditions in the mock-up were controlled and measured. It was found that specSE can be considered as a distinct construct and that it contributed substantially to the prediction of thermal comfort and climate satisfaction. In addition, it moderated the effects of available and exercised control. The presented results expand upon earlier findings for the concept of personal control and confirm the role of specSE for thermal comfort predictions.

Thermal comfort, Climate satisfaction, Personal control, Perceived control, Thermo-specific self-efficacy, Environmental psychology, Long-distance trains

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1 Thermal comfort in long-distance trains

Considering the growing importance of climate change in current discussions about future transport, railways have the potential to increase their market share [1],[2]. To strengthen their popularity for the passengers, railways have to provide an attractive environment that takes the passengers reliably and comfortably from A to B. One important aspect determining the attractiveness of long-distance rail journeys is the thermal comfort that is provided in a passenger rail car [1],[3]-[5]. In their day-to-day business, railway cars are subject to transient conditions. Rapid changes in passenger density or thermal loads caused by extreme weather conditions can alter the indoor climate situation at short notice [6]. The indoor climate situation immediately influences the passengers' well-being as it can cause discomfort due to heat, cold or air draughts for example. To avoid these, comfort parameters are defined in relevant norms to ensure that thermal comfort is provided at best in different environmental scenarios (e. g. [7]: In EN 13129, comfort parameter definitions are given for "main line rolling stock", i.e. long-distance trains. Parameters are defined explicitly for the occupants' zone of rail cars and relate to sedentary persons; for example, mean air temperature may vary between 22 °C and 27 °C depending on outside temperatures. As a function of the mean indoor air temperature, air velocity can vary between 0.25 m/s and 0.6 m/s, and relative humidity may vary between 45 % and 65 %).

Railway industries have an interest in determining the thermal comfort in railway vehicles at a very early stage of the design process to avoid expensive subsequent optimization processes [8],[9]. Simulation studies contribute to a better understanding of the effects of air-conditioning and ventilation techniques on rail passengers' comfort in future long distance trains [10],[11]. Up to date, only a few empirical studies deal with the thermal comfort that is perceived by railway passengers [12],[4]. From the findings published so far it can be concluded that the indoor climate environment and thus thermal comfort in railway cars is diverse and multidimensional as it is the result of complex interactions of different internal and external factors. Up to now, the focus is on providing a globally comfortable indoor climate situation for the passengers. This approach ignores inter-individual differences between the passengers and cannot satisfy individual preferences which have a strong potential to influence thermal perceptions and evaluations [13]. However, personalized comfort zones are a promising approach to gain competitive advantage over alternative means of transport. Another benefit could be the reduction of energy demands by a purposeful and effective air conditioning.

1.1 Personalized comfort zones in passenger cabins

Personalized comfort zones enable the users to take control of their immediate indoor climate environment. In office buildings, available control can be exercised for example by opening windows, blinds, operating HVAC (heating, ventilation, air conditioning) systems, fans or manipulating the insulation from personal clothing. In long-distance trains, the available controls are reduced to just blinds and personal clothes and in some cases HVAC related control devices, when these can be regulated in single compartments. Little research has been published relating to personalized comfort zones in railway vehicles so far: In Schmeling et al. [14], the effect of locally installed infrared (IR) heating panels in combination with cabin displacement ventilation (CDV) was analyzed [13]. It was confirmed that the IR-panels compensated for the cold-feet-effect of floor-based CDV and led to an increased comfort, especially for women. Research that addressed personalized air-conditioning in buildings has a longer history (e.g. [15],[16]) but lessons-learned cannot be easily transferred to vehicle cabins or railway compartments respectively: in these, inhomogeneous and transient indoor climate conditions are common which does not correspond to the conditions in buildings (see also [12]). Some knowledge can be gained from research in aviation and vehicular sciences. For aircraft cabins, e.g. You et al. compared the performance of personalized displacement ventilation with mixing and conventional displacement ventilation systems via CFD simulations [17], [18]. They found that personalized ventilation was the system that created the best cabin comfort and reduced the risk of possible infections. These results confirmed earlier findings by Zhang and Chen, who made a similar comparison and found that personalized ventilation also provided the most effective CO_2 reduction without creating higher draughts [19]. Fojtlín et al. analyzed the benefit of individual sensors for equivalent temperatures in vehicle cabins [20]. As the authors state, in the future, the system outputs could be used for “comfort driven control actions of the cabin HVAC system”, resulting in a “personalized thermal comfort experience” (p. 68). Metzmacher et al. described an innovative approach to realize personalized air conditioning in vehicles. They combined contactless thermal comfort measurements and simulated real-time data [21]. Thermal comfort was provided by placing infrared heating panels and individual fans in the immediate environment of a thermal manikin.

Summing up the results from current research, implementing personalized comfort zones has the potential to increase thermal comfort and air quality in vehicles – it will likely also be successful for railway passengers. The question is under which conditions personalized comfort zones may improve thermal comfort and passenger satisfaction. Does handing over control of the thermal environment to railway passengers necessarily lead to higher comfort? Taking a psychological approach to these questions should help to identify conditions that account for the (positive) effects of personalized comfort zones on thermal comfort.

1.2 The concept of personal control and thermo-specific self-efficacy

A promising concept for the analysis of psychological factors that could account for the efficacy of personalized comfort zones is the concept of personal control, which is already widely accepted in thermal comfort research [22], [23]. Personal control is determined by available control opportunities and by personal preferences and behavioral patterns [22]. Paciuk distinguishes between available, exercised and perceived control: Available control refers to the degree and type of control opportunities made available to the occupants, for example features as opening windows, doors, blinds, sunshades, fans and thermostats. Exercised control is defined as the relative frequency with which occupants engage in manipulative (e.g. adjusting environmental parameters) and adaptive behaviors (e.g. adjusting one’s clothes or activity) to maintain thermal comfort. Perceived control refers to the perception of available control opportunities and feedback of their effectiveness [23].

Perceived control of the environment is well known to positively influence (thermal) comfort in buildings. For office buildings it was found that the *perceived* degree of control was one of the most important predictors of thermal comfort; further, it had a significant effect on satisfaction [24], [25]. Frontczak and Wargocki [26] undertook a literature survey on factors that influence human comfort in indoor environments. Three studies confirmed the influence of *available* control on thermal comfort: in only one study there were no effects of control. Frontczak and Wargocki [26] reported that "providing people with the possibility to control the indoor environment improves thermal and visual comfort and overall satisfaction with IEQ [indoor environmental quality] as well as satisfaction with indoor air quality" (p. 936). Brager et al. found that occupants who were able to open the windows of their offices had more *available* control and therefore a higher *perceived* control than occupants in centrally controlled office environments [27]. The authors concluded that people in naturally ventilated buildings associated with a wider degree of available control were more satisfied.

As mentioned by Hellwig, it is often argued that personal control is not necessary as it should be the aim of engineering to build thermo-static systems that adapt to people's individual thermic needs, so there is no need to exercise individual control on thermal conditions [22]. This view is in line with one finding of Boerstra et al. [28]: In an experimental study, participants perceived higher control but no higher comfort when they regulated a fan by themselves. In the second experimental condition, the fan was regulated by the test conductor in the same way as the participant had done in the first condition two weeks before and participants felt equally comfortable. If personal control led to higher comfort even when all thermal conditions are equal, participants should have felt more comfortable in the first condition. Thus, it may not be the psychological effect of having control that accounts for a higher thermal comfort. Rather, available control could be the means for the individual to fine-tune thermal conditions so that they are optimal for his or her comfort. Whether these optimal conditions are controlled individually or externally may not be crucial. In summary, these findings indicate that there is no direct relationship between perceived control and thermal comfort. As Boerstra [29] discussed, the relationship seems to be more complex.

In most empirical studies, the focus is on physical controls [30]. Nonetheless, perceived control is related not just to real control opportunities but also includes psychological aspects: People with the same amount of available control opportunities may vary in their behavior in two ways. Firstly, people have different tolerances for acceptable thermal conditions. For some people it is not necessary to adapt the temperature so often because they are satisfied with a wider range of temperatures [31]. Secondly, people have different expectations in their abilities to influence indoor climate conditions. A person who is not familiar with HVAC systems may hesitate to adjust it. An anxious person may be hesitant to close a window in an occupied train because that could annoy other passengers. Hellwig introduced the psychological concept of self-efficacy for indoor environment related comfort research [22] in order to explain interpersonal differences in expectations and behavior. Hawighorst et al. [32] labelled the corresponding psychological concept as “thermo-specific self-efficacy” (specSE). SpecSE describes peoples' expectations towards their competence to execute effective operations to improve thermal conditions in their environment successfully. It includes knowledge about identifying and controlling thermal parameters, social competencies for addressing and convincing other people who will be affected by changes of thermal parameters, and their own level of acceptance for suboptimal thermal conditions. In contrast to perceived control, specSE stands for the personal belief in one’s own competencies which are stable over time and over different situations. Perceived control is more dependent on the situation, for example the perception of available control opportunities. Hawighorst et al. [32] conducted several studies in field and laboratory environments in which it was possible to control the indoor climate conditions by opening the window or using blinds or a fan. People with a low level of specSE felt warmer and thus less comfortable than people with high specSE. Perceived control and effectiveness of controls in buildings differed between people with high and low self-efficacy. In laboratory experiments by the same authors, differences in thermal preferences indicated that people who thought they could control their thermal environment were more satisfied with their thermal situation and wanted less changes of the conditions than people who thought they were not able to execute control [33]. Although Hawighorst et al. [32] stressed the impact of specSE on thermal comfort it remained unclear to what extent specSE accounts for differences in perceived comfort (in

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contrast to available control). It has to be clarified if specSE can be strengthened as a distinct concept and explanatory factor regarding thermal comfort.

1.3 Aims and scope

In this paper, two studies are presented that focused on contributing to a better understanding of the role of personal control for thermal comfort in long-distance trains. The aim was to explore the construct of “thermo-specific self-efficacy” (specSE). It was hypothesized that a higher specSE regarding the thermal environment in railway cars would lead to higher thermal comfort and higher satisfaction with the climate situation therein. SpecSE should contribute to a significant extent to the prediction of indoor climate satisfaction in addition to the comfort evaluations of relevant thermal parameters. Moreover, we hypothesized a difference in climate satisfaction between people with high and low specSE depending on whether control options over the immediate indoor climate situation were available or not.

2 Study 1

In the first study, our hypotheses were examined by analyzing thermal comfort in a railway car and assessing specSE as additional factor. This variable was used in addition to thermal comfort evaluations to predict the satisfaction with the indoor climate situation.

2.1 Method

Study 1 included eight human subject test runs, each with two experimental conditions (two temperatures, see Flowchart). These took place between 2015 and 2017 in a mock-up of a passenger rail car of the Next Generation Train (NGT; see Figure 1). Its cabin interior comprised 24 seats in six rows and an external environmental control system that allowed adjusting air temperature and volume flow rates. The ventilation system was variable and different air outlets could be used for air supply without the option for individual adjustments.

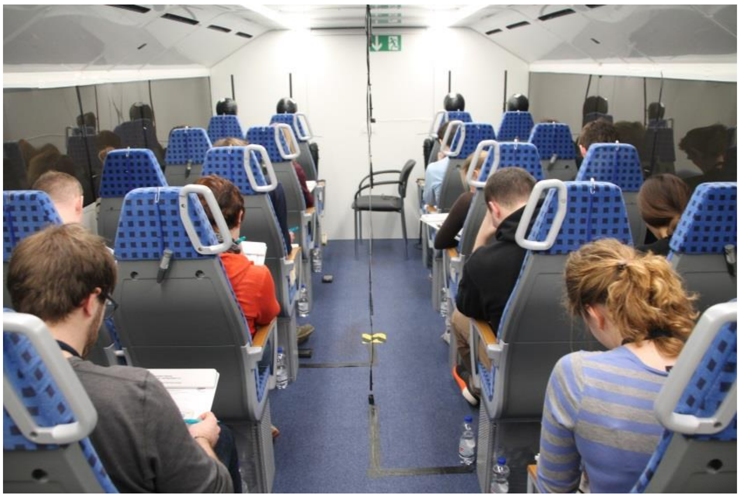

Figure 1: Test subjects in the passenger rail car mock-up.

In the first four runs, fresh air was supplied via cabin displacement ventilation (CDV) outlets that had been installed under the passengers' seats. The exhaust air left the cabin through slit-shaped outlets in lateral regions of the ceiling (for a detailed description of the ventilation system see [34]). The four CDV runs included eight experimental conditions, in which different temperatures (intended range 20 to 29 °C) were operationalized. In the fifth and sixth run, microjet ventilation (MV) was used. In these two MV runs four experimental conditions with intended temperatures between 20 and 26 °C were examined. In the seventh and eighth run, fresh air was supplied via hatrack-integrated low momentum ventilation (HLMV). These two runs included four experimental conditions with intended temperatures between 21 and 26 °C. The temperature range was chosen to cover a broad temperature spread and to achieve variance in comfort values (see Figure 2). The volume flow of air was constant with 230 l/s (= 9.2 l/s per person) and relative humidity (rH) was to be kept below the maximum values that are defined in EN 13129 [7] for the different temperature levels used (rH < 65 % for temperatures ≤ 23 °C and rH < 45 % for temperatures ≤ 29 °C).

To achieve comparable ventilation conditions for the passengers in the first row, four thermal passenger dummies were placed in row zero. These were electrically heated and emitted the same amount of sensible heat like real passengers (75 W). Outside temperatures were on average 10 °C.

2.1.1 Sample

The recruitment of participants was undertaken with the help of a service contractor via an online panel. All in all, 160 subjects participated in this study; 20 in each run. Half of the subjects were female (n = 79), half male (n = 81). The subjects' age ranged between 18 and 63 years (M = 33.8 years, SD = 12.2 years), their height between 155 cm and 190 cm (M = 175.2 cm, SD = 8.9 cm) and their mean BMI was 24.4 (SD = 4.8). All participants were advised in advance to wear shirts with long sleeves, long trousers, and ankle free shoes. Scarfs were not allowed. Thus, we aimed at ensuring equivalent clothing conditions (≙ 0.8–1 clo). For their participation, subjects were compensated monetarily after the run.

2.1.2 Questionnaire and measurement equipment

Subjective data were assessed using standardized rating techniques. Items were administered on PDAs (HP iPAQ214, input by stylus pen). Participants rated the comfort level of four indoor climate parameters, namely air temperature, air velocity, humidity and air quality, using a five-point scale, ranging from 1 = very uncomfortable, 3 = neutral to 5 = very comfortable. In the following sections we will refer to these ratings as "thermal comfort". Finally, a general indoor climate satisfaction judgment was given on a five-point rating scale ranging from 1 = very dissatisfied to 5 = very satisfied. We will refer to this judgement as "climate satisfaction".

For the assessment of thermo-specific self-efficacy (specSE) in long-distance trains, a new 10-item-questionnaire was developed. Items were phrased railway-specific and address a person's locus of control as well as self-efficacy beliefs. The items had to be answered on a six-point Likert scale ranging from 1 = I totally disagree to 6 = I totally agree. We included six items that addressed a high

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degree of specSE in a railway passenger carriage (e. g. “On the train, I always have the option of creating a comfortable temperature.”) and four items that addressed a low degree of specSE (e.g.: “My well-being on the train depends to a large extent on the quality of the air conditioning.”, see Appendix A). The questionnaire is focused on passenger’s general experiences and expectations for railway journeys and not on their current experience with the mock-up train used for the experiment. For the following analyses, items were aggregated by using the factor scores of the first unrotated factor derived from a factor analysis (Cronbach’s alpha = 0.69).

In addition to subjective data, objective data were gathered by various sensors to document the passenger carriage climate. Air temperature and relative humidity were assessed with data loggers at each passenger seat and at the cabin center at a height of 110 cm. This allowed the calculation of the mean air temperature (T_{IM}) according to EN 13129 [7]. Air velocity was measured using omnidirectional sensors in a replication of the test scenarios with 24 thermal passenger dummies (75 W constant heat release), as the sensors’ arrangement close to different human body parts would have restricted the subjects’ mobility.

2.1.3 Experimental design and procedure

In each test run, one ventilation setting was administered using two different temperature scenarios. Both scenarios were presented twice to gain a reliable dataset: first, the warmer scenario was presented twice, then, the temperature was changed, and the colder scenario was presented twice (see Figure 2). This method minimized the temperature transition times and maximized the stability and comparability of the corresponding temperature scenarios which were averaged for statistical analyses.

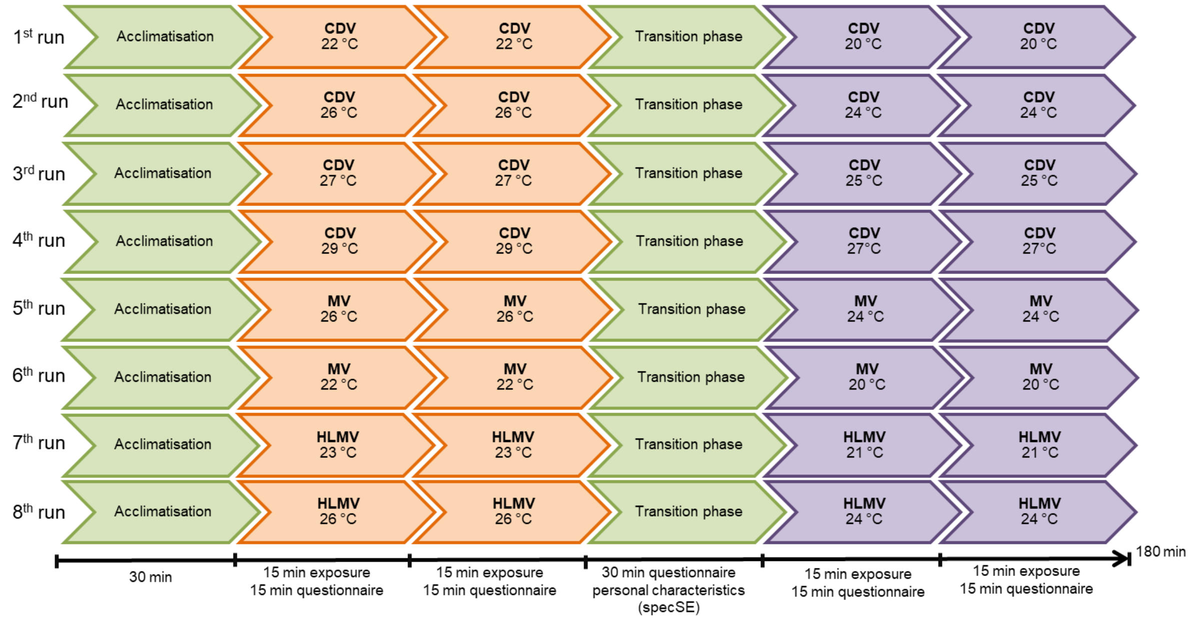

Figure 2: Experimental protocol for Study 1

The procedure followed the same schedule in each run: Participants were welcomed and guided into the mock-up. There they were provided with instructions and they had time to familiarize themselves with the PDAs while also acclimatizing to the climate. In the meantime, the target climate was adjusted (acclimatization phase). When the climate was stable, the experimental phase started and each scenario was presented for 30 minutes in total. In the first 15 minutes, subjects were entertained by solving crosswords and Sudoko grids in a magazine. During the last 15 minutes of the exposure time, they filled out the comfort questionnaire while the climate remained unchanged. Subsequently, the next temperature scenario started. In the transition phases between the warmer and the colder climate, snacks were offered and questions about personal characteristics (including specSE) were answered. The whole procedure lasted about three hours.

2.2 Results

2.2.1 Objective climate situation in the passenger rail car

For the description of the objective climate situation in the passenger rail car, objective measurements were averaged per ventilation setting. The average cabin temperature (T_{IM}) ranged between 21.3 °C and 28.8 °C (SD 0.4 °C) and thus covered the range of nominal values given for room air temperatures in EN 13129. Relative humidity was kept inside the comfort zone defined in EN 13129 and varied from 23.8 % to 51.7 % (SD 1.7 %). Air velocity was very low (max. 0.17 m/s), especially in the climate scenarios using CDV (0.05 m/s, SD 0.02 m/s). It corresponded to the maximum standard values given in EN 13129 in all scenarios.

2.2.2 Prediction of satisfaction with the railway carriage climate

As all assessments took place in the same mock-up and in the same experimental setting, the data were averaged over all climate scenarios to increase statistical power. Analyses of climate evaluations for single scenarios can be found in [35]. Descriptive statistics for the dataset are presented in Table 1. Participants rated their thermo-specific self-efficacy between 2 and 5.2 with a mean of 3.28 – this is close to the centre of a 6-point scale.

Table 1. Descriptive statistics for questionnaire data.

	N	Min	Max	Mean	SD
Climate comfort					
Temperature evaluation	160	1.25	5.00	2.87	0.85
Air draught evaluation	160	1.00	5.00	3.07	0.79
Humidity evaluation	160	1.00	5.00	2.92	0.71
Air quality evaluation	160	1.00	5.00	3.04	0.78
Satisfaction with the climate situation	160	1.45	4.99	3.09	0.67
SpecSE	159[1]	2.00	5.20	3.28	0.55

Note: [1]One data set was partially lost during the assessment.

Pearson correlation coefficients were calculated to identify the interrelationships between variables. Results are presented in Table 2. Significant correlations were observed between all thermal comfort ratings and satisfaction with the climate. The highest correlations were found between temperature evaluation, air draught evaluation and satisfaction with the climate and between air quality evaluation and humidity evaluation. For specSE, only the relationship with the climate satisfaction was significant: The higher the subjects' thermo-specific self-efficacy, the more satisfied they were.

Table 2. Bivariate correlations for thermal comfort, satisfaction and specSE.

		Thermal comfort ratings			
	Climate Satisfaction	Temperature	Air draught	Humidity	Air quality
Temperature evaluation	.76**	1			
Air draught evaluation	.61**	.68**	1		
Humidity evaluation	.54**	.39**	.37**	1	
Air quality evaluation	.46**	.29**	.20*	.63**	1
SpecSE	.21**	.10	.15	.06	-.02

Note: * p < .05, ** p < .01.

To identify the relative importance of thermal comfort ratings and specSE for the satisfaction with the indoor climate situation, a hierarchical multiple linear regression analysis was calculated [36].

In Model 1, the satisfaction with the climate situation was predicted by the four thermal comfort ratings. To determine the incremental value of specSE for the prediction function, this variable was entered as additional variable in Model 2. Results are presented in Table 3.

Table 3. Prediction of climate satisfaction using multiple linear regression modelling.

Model	DV	IV	*B*	*ß*	*R*	*F*	*df*	R^2 (R^2adj.)
1	Climate satisfaction				.82**	81.57	4; 154	.68 (.67)
		Intercept	0.55					
		Temperature evaluation	0.44	.55**				
		Air draught evaluation	0.12	.14*				

		Humidity evaluation	0.15	.16*				
		Air quality evaluation	0.15	.18**				
2	Climate satisfaction				.83**	70.35	5; 153	.70 (.69)
		Intercept	0.59					
		Temperature evaluation	0.44	.55**				
		Air draught evaluation	0.11	.13*				
		Humidity evaluation	0.14	.15*				
		Air quality evaluation	0.16	.19**				
		SpecSE	0.09	.13**				

Note: * p < .05, ** p < .01.

Significant regression lines were obtained for both models (see Table 3). All included predictor variables had a significant weight for climate satisfaction, with temperature evaluation being the most relevant predictor. The inclusion of specSE as a further predictor added a significant amount of explained variance to the regression ($p_{change} < .01$). That means specSE was a relevant construct for the prediction of climate satisfaction in the train passenger cabin mock-up adding to the predictive power of the thermal comfort ratings.

2.3 Discussion

It is generally assumed that personal control over indoor climate settings contributes to the passengers' satisfaction or thermal comfort respectively. Usually, railway travelers do not have many options to influence the thermal conditions in a rail passenger car. Besides adapting one's clothes or using the blinds only some train compartments provide adjustable control panels for the HVAC-system. The current study investigated the relationship between personal control and thermal comfort as well as indoor climate satisfaction empirically by taking a psychological approach and considering the personality trait "thermo-specific self-efficacy" as an additional variable for the prediction of thermal comfort. Human subject tests were carried out in a mock-up of a passenger rail car of the Next Generation Train (NGT).

Significant interrelations between thermal comfort ratings reflected the high interdependency of thermal comfort parameters and the complexity that challenges precise thermal comfort predictions in general. The more comfortable single parameters were rated, the higher was the passengers' climate satisfaction. This was further reflected in the relative weights of thermal comfort ratings in the regression analysis. Temperature evaluation had the highest weight which confirmed its relevance for the prediction of the satisfaction with the climate situation (Table 3). This corresponds to classic approaches for the prediction of thermal comfort as can be found in the common standards (e.g. [7]).

In the second step, the role of thermo-specific self-efficacy (specSE) was elaborated on. Participants answered in a range from 2 to 5.2 on the specSE scale. This is noteworthy, because in long-distance trains, nearly no control for thermal comfort is available. Nevertheless, participants differed in their beliefs to control their personal comfort in a train. No meaningful correlations with the single thermal comfort ratings were found. Nonetheless there was a positive relationship with the overall climate satisfaction suggesting the relevance of perceived control. These results support Hellwig's conceptual model of perceived control [22] where locus of control and self-efficacy are contributing factors to perceived control and perceived control is the key factor for the evaluation of satisfaction. Perceived control can alleviate discomfort and then can lead to satisfaction although not directly to thermal comfort. Consequently, in the regression analysis, specSE contributed substantially to the prediction of climate satisfaction in addition to thermal comfort ratings (Table 3). Subjects who described themselves as having higher specSE were more satisfied with the indoor climate than subjects with low specSE. Of special interest was the observation that the effect of specSE on climate satisfaction is as high – that means as relevant – as the effect of the thermal comfort ratings for air draught and humidity. In long-distance trains, which were the context of our studies, there might of course be additional factors influencing the effects of specSE on passengers' thermal comfort, which were not part of the current study. One might assume that a higher passenger density is detrimental to specSE as well as travel duration or a dense seating arrangement with little privacy. Moreover, there might be changing demands during long-distance travels that might be more easily addressed by passengers having a higher feeling of control. For the near future, we have planned to assess more data on specSE in a real passenger cabin where we will consider the passenger density, for example. Up to now, we can confirm that the psychological construct specSE determines climate satisfaction alongside of physical (but subjectively evaluated) indoor climate conditions: Passengers who have a high sense of being able to control their thermal surrounding (= high specSE) will generally tend to be more satisfied with indoor climate conditions, even if these are tending towards uncomfortable extremes. This extends the results of Luo et al. [31] who found that having control led to a wider range of acceptable temperatures. In the present study, even people who merely believed they generally have control and can influence thermal conditions felt more comfortable, although they actually did not have any control. A possible explanation is that locus of control expectancies and self-efficacy beliefs are strongly correlated with life satisfaction and optimism [37], and that passengers who are more satisfied and optimistic might also be less critical with indoor thermal environments.

Limitations to our results arise because of the experimental setting we worked in: The mockup was equipped rather simply with seats taken from a German regional train. These were of course not directly comparable with long-distance train seats, but as the focus of our research was on the effects of specSE on thermal (and not seating) comfort, we assume that the seating design did not systematically interact with our results. Nevertheless, the narrower seating arrangements in regional trains and the missing possibility of adjusting the seats' back might influence the privacy and therefore the passenger comfort. Yet, in future research, we plan to assess data in a real ICE passenger car to enhance the external validity of our research. A further limitation to the external validity can be seen in the clothing restrictions we had to put onto the passengers during the experiment. To keep thermal conditions constant for all participants and control for unwanted thermal effects, subjects did not have any possibilities to change their clothing level, which would be different on a real long-distance train journey.

3 Study 2

The second study also took place in the mock-up of a passenger rail car of the NGT described above (see Figure 1). In this study, the intention was to vary the amount of available control the passengers had over their thermal environment. Therefore, remotely controllable IR heating panels were installed in the mock-up (see Figure 3). We assessed the effects of available and exercised control on climate satisfaction via questionnaires and observations.

3.1 Method

Four seats in the mock-up were equipped with remotely controllable IR heating panels (size about 0.3 m x 0.3 m). These were mounted to the side walls, the floor area, and to the backrests of the front seats in the passengers' immediate environment (see Figure 3). Three test runs each with four experimental conditions took place in March 2018. The ventilation system used was CDV with an intended T_{IM} of 20 °C. Outside temperatures were on average 7 °C.

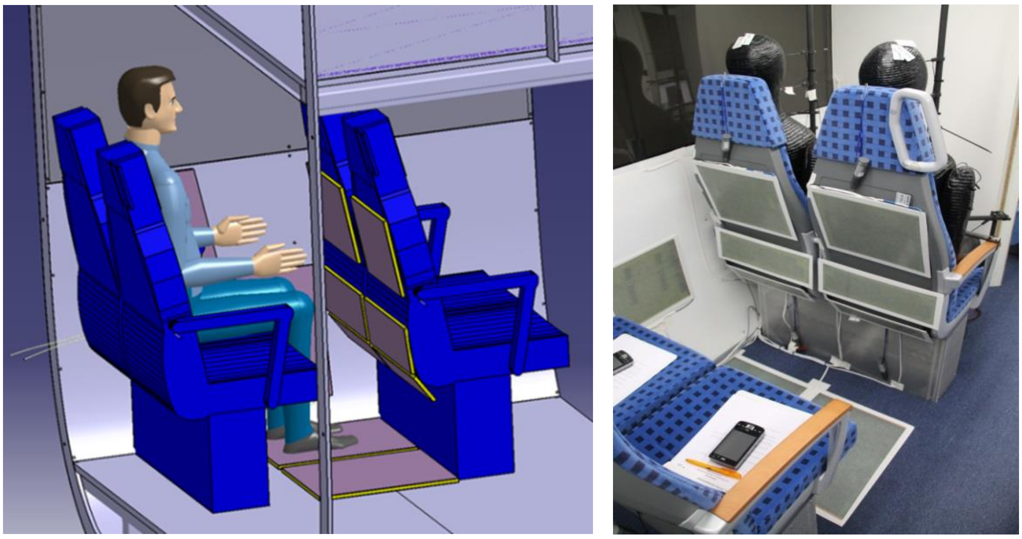

Figure 3: Configuration of the IR heating panels in the NGT mock-up.

3.1.1 Sample and measurement equipment

In Study 2, 12 subjects took part (6 female, 6 male); 4 subjects in each run. Because of the required installations of several components for such a personalized indoor climate control system, this experimental study could only be conducted with a smaller sample. The subjects were between 19 and 53 years old (M = 34.8 years, SD = 11.3 years), their height ranged between 166 cm and 186 cm (M = 177.6 cm, SD = 7.2 cm) and their mean BMI was 26.6 (SD = 4.9). One subject had a slight cold during the run. Again, the recruitment of participants was undertaken via an online panel. Participants wore standardized clothing and were compensated monetarily after the run.

For the data assessment, the same standardized measurement equipment was used as described for Study 1 (see 2.1.2).

3.1.2 Experimental design and procedure

Two scenarios as illustrated in Figure 4 were undertaken. The first scenario (without individual control) had three phases, which were aggregated for the analyses. Between phases, IR-panels were switched “on” and “off” in three configurations varying from just one panel per seat “on” to all three panels per seat “on”. The order of the three IR-panel configurations was rotated over the three test runs according to the experimental protocol to balance possible order related effects. Exposure time was 20 minutes in total for each configuration. In the first 10 minutes, subjects were entertained by solving crosswords and Sudoko grids in a magazine. During the last 10 minutes of the exposure time, they filled out the comfort questionnaire while the indoor thermal environment remained unchanged. Subsequently, the next configuration was realized. Subsequent to scenario 1, a 10-minute break was scheduled to administer a short personality questionnaire and to collect the specSE data. Following this break, scenario 2 (individual control available) was presented: During the single phase of scenario 2, all subjects had a remote control device in their hands to manage the heating level of each of their seat related IR-panels (range: “off”-“medium”-“full”) at the beginning of the exposure phase. When all subjects had found their optimal configuration, the indoor climate remained stable until the end of the scenario. During the last 10 minutes of the exposure time, subjects filled out the comfort questionnaire. Data for the heating control inputs were logged for each subject.

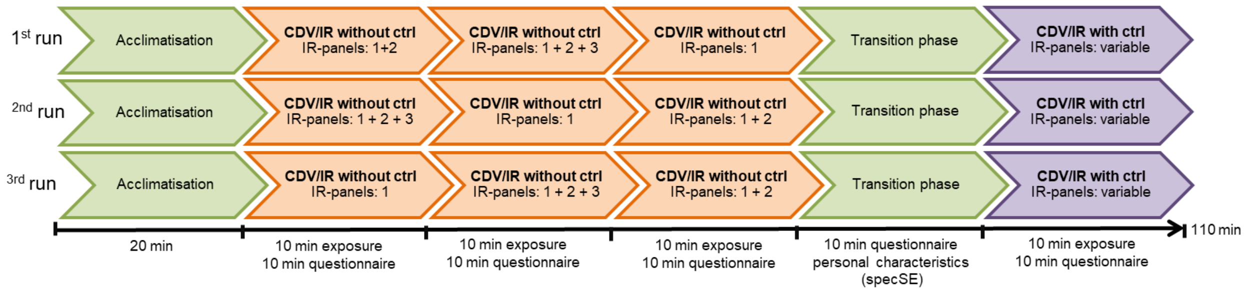

Figure 4: Experimental protocol for Study 2

3.2 Results

3.2.1 Objective indoor climate situation in the passenger rail car

For the description of the objective indoor climate situation in the passenger rail car, objective measurements were averaged per scenario. The average cabin temperature (T_{IM}) was 21.5 °C (SD 0.7 °C), mean relative humidity 38.3 % (SD 4.6 %) and mean air velocity 0.05 m/s (SD 0.01 m/s) during scenario 1. In scenario 2, T_{IM} was 21.7 °C (SD 0.4 °C), mean relative humidity 37.8 % (SD 5.3 %) and mean air velocity 0.05 m/s (SD 0.01 m/s).

3.2.2 Effects of available and exercised control on climate satisfaction

Based on the specSE scale, subjects were split at the median into two groups of six. Group 1 assumed low specSE regarding comfort conditions during train rides while group 2 assumed high specSE. To examine the effects of the two factors of specSE (group 1 or 2) and available control (provided or not provided) on the dependent variable of climate satisfaction, a mixed model ANOVA was conducted. In this study the main effects of both independent factors were not significant ($F_{(1,10)} = 1.6$, $p > .10$, $\eta^2_p = 0.13$ for available control and $F_{(1,10)} = 2.8$, $p > .10$, $\eta^2_p = 0.22$ for specSE). There were no significant differences between subjects with high or low specSE and no differences in relation to the availability of control. However, the interaction of the independent factors specSE and available control had a significant effect on climate satisfaction: the associated F-statistic of $F_{(1,10)} = 14.0$ was significant with $p < .01$ and an effect size of $\eta^2_p = 0.58$. As shown in Figure 5, the climate satisfaction scores of the group with low specSE during train rides rose substantially when they could manage the heating control themselves (i. e. available control). Climate satisfaction scores of the high specSE group remained statistically unchanged under these conditions ($t_{(5)} = 1,63$, $p > .10$).

To find out to what extent control inputs were actually executed (exercised control) the remote-control log files were analyzed. It was confirmed that the subjects in the low specSE group manipulated the heating levels of the IR-panels 1.4 times more often than subjects in the high specSE group. Thus, the data indicate a correspondence between actual execution of heating control and the subjects' climate satisfaction.

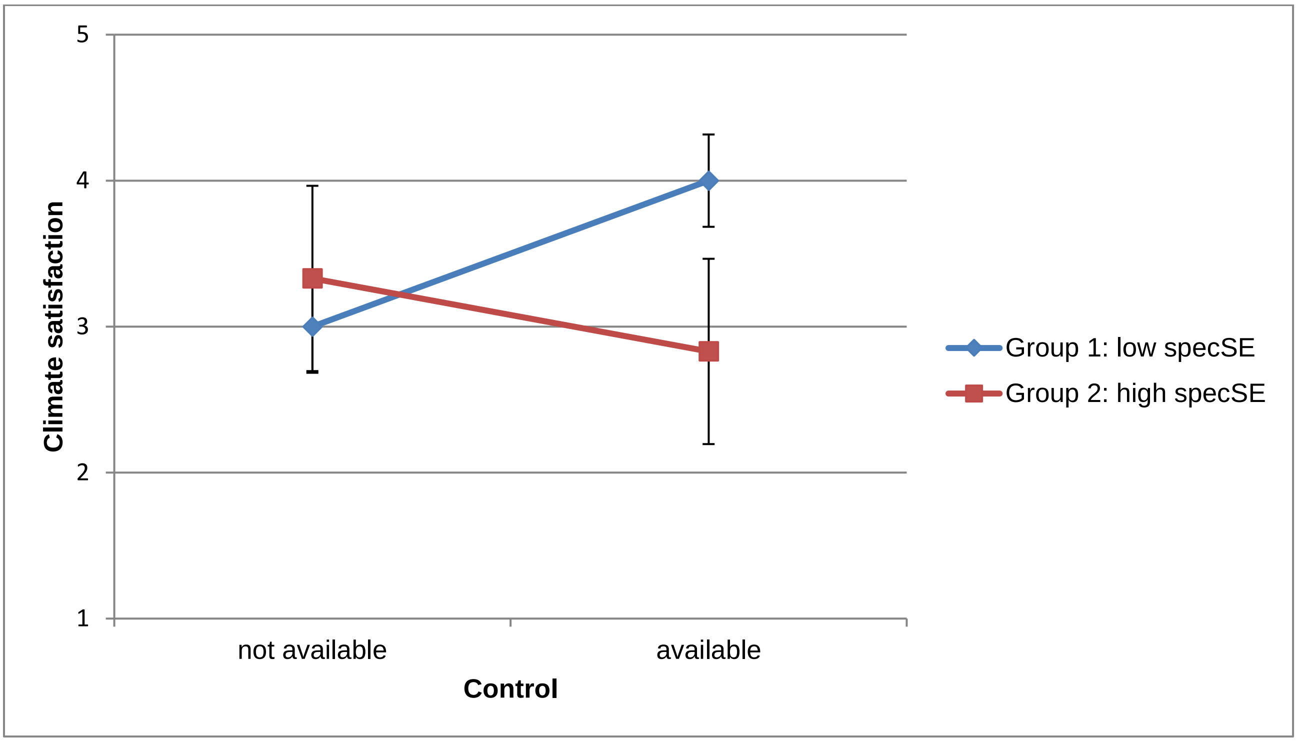

Figure 5: Effects of control and specSE on climate satisfaction (1 = very dissatisfied to 5 = very satisfied). The error bars indicate the standard deviation of the respective scores.

3.3 Discussion

In Study 2 it was shown that there was no general difference in climate satisfaction depending on whether subjects were just given control over IR heating panels in their immediate surrounding or not. At a first glance, this contradicted our expectations (see 1.3) and earlier research (e. g. [26]). Looking at subjects' specSE scores, it became clear that this construct moderated the relationship between available/exercised control and climate satisfaction: When subjects were given control, those who were predominantly low in specSE profited significantly more. This is in line with earlier results showing that subjects with low specSE preferred having more control than subjects with high specSE [32]. They executed more control and reported higher climate satisfaction than they did in the condition without control. For subjects with high specSE, the degree of climate satisfaction remained the same and there was no additional benefit of the availability of control. This might be explained by taking into account the subjects' acceptance threshold [32],[38]: Those having low specSE were generally rather dissatisfied with the lack of control they normally had in railway cars. Apparently, their acceptance threshold was rather low and they appreciated when they were given control over their microclimate. As a result, they gave higher satisfaction ratings. Compared to this, those with high specSE felt they were in control even if there was no available control. This interpretation goes along with earlier findings, where subjects with higher specSE had a higher acceptance threshold [32] and people with higher acceptance threshold felt more comfortable even in the condition where they didn't use the available controls [38]. In this context, it should be mentioned that Boerstra [29] presented a conceptual model in which perceived control (as the situation-related counterpart of specSE) can act as a moderator for the relation between thermal conditions and climate satisfaction. According to this model, the amount of perceived control can amplify or diminish the significance of the local indoor climate for comfort and satisfaction in addition to possible direct effects.

A limiting factor of Study 2 is the small sample size, which reduced the power of the statistical tests so that smaller effects might remain concealed. Therefore, a possible direct effect of specSE on climate satisfaction, which was found in Study 1 could remain undetected in Study 2. The challenge persists to provide further evidence of the direct and indirect effects of personal control for passenger comfort and satisfaction with a larger number of participants.

4 Conclusion

To date, the main research focus for the prediction of thermal comfort has been on the role of perceived, available and/or exercised control (e. g. [24]–[28]). In Study 1, specSE influenced climate satisfaction without correlating with the thermal comfort ratings. This result supports Hellwig's model of perceived control [22] where thermal comfort is mainly achieved by homeostasis, while climate satisfaction is dependent on thermal comfort and the psychological evaluation system, which includes locus of control expectancies and self-efficacy beliefs. Our results from Study 2 show that the concept "specSE", not only directly influences climate satisfaction but also moderates the effects of available and exercised control on climate satisfaction. This can explain why providing individual temperature controls to users does not necessarily lead to higher thermal comfort as shown by Karjalainen et al. [39]. The results presented here further expand upon earlier findings for this construct [32] and the concept of personal control. At first glance, installations of individual control devices and auxiliary heating or cooling panels will require additional resources. As a preliminary estimate of the required energy costs for the configuration used in our study indicated, it seems to be a reasonable solution only for separate personal comfort zones with preferred customers [35]. On the other side, personalized air conditioning devices with individual control could also be an option to extend the comfort envelope within a rail car. If for example the acceptable range of comfort parameters – as specified by the normative requirements – would be extended in unoccupied areas, passengers could adapt the local conditions to their personal needs. This would provide positive effects on the total energy costs [16][35].

Moreover, our findings yield the idea that evaluations of thermal comfort are always subject to inter-individual differences. Even if some long-distance railway cars are designed to provide thermal control options for the passengers, and thus have the potential to create individually comfortable microclimates, personal characteristics will always play an important role for the judgement of thermal conditions. In case of specSE, it might be worth to consider ways to enhance the personal feeling of being in control by providing specifically customized information, suitable guidance or other service options.

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Appendix A. Questionnaire “Thermo-specific self-efficacy on the train”

This appendix presents the German and the English version of the questionnaire “Thermo-specific self-efficacy on the train”. The German version was used for both studies presented in this paper. Answers are given on a 6-point-scale “1 = stimme überhaupt nicht zu, 2 = stimme nicht zu, 3 = stimme eher nicht zu, 4 = stimme eher zu, 5 = stimme zu, 6 = stimme voll und ganz zu” (“1 = I totally disagree, 2 = I disagree, 3 = I rather disagree, 4 = I rather agree, 5 = I agree, 6 = I totally agree”).

Table A1.
German version: “Thermo-spezifische Selbstwirksamkeitserwartung in der Bahn”

Item	Statement
1	Ob ich mich während einer Zugfahrt wohlfühle, hängt von mir ab.
2	Zufällige Klimaeinstellungen bestimmen mein Wohlbefinden im Zug.
3	Ich kenne viele Möglichkeiten, mir die Zugfahrt angenehm zu gestalten.
4	Für meine Behaglichkeit im Zug ist das Zugpersonal verantwortlich.
5	Ich kann im Zug selber bestimmen, wie warm oder kalt es sein soll.
6	Mein Wohlbefinden im Zug hängt im starken Maße von der Beschaffenheit der Klimaanlage ab.
7	Es hängt hauptsächlich von mir ab, ob mir im Zug zu warm oder zu kalt ist.
8	Ich habe im Zug stets die Möglichkeit, eine wohlige Temperatur herzustellen.
9	Es hängt hauptsächlich von der Beschaffenheit des Zuges ab, ob mir im Zug zu warm oder zu kalt ist.
10	Es ist mir im Zug immer möglich, ein angenehmes Klima einzurichten.

Table A2.
English version: “Thermo-specific self-efficacy on the train”

Item	Statement
1	It depends on me whether I feel comfortable on a train ride.
2	Random climate settings determine my well-being on the train.
3	I know many ways to make my train journey pleasant.
4	The train staff is responsible for my comfort on the train.
5	I can decide for myself how warm or cold it should be on the train.
6	My well-being on the train depends to a large extent on the quality of the air conditioning.
7	It mainly depends on me whether the train is too warm or too cold for me.
8	On the train, I always have the option of creating a comfortable temperature.
9	It mainly depends on the nature of the train whether the train is too warm or too cold for me.
10	It is always possible for me to create a pleasant indoor climate on the train.

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Conflict of interests

The Authors declare that there is no conflict of interests.

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