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Multi-jet personalized ventilation in passenger trains: Objective and subjective thermal comfort

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ABSTRACT

Installing local, individually controllable ventilation – a specific version of a personalized environmental control system – offers great potential in terms of improving the individual thermal comfort and energy savings of the overall train air-conditioning system. In our experimental investigation, we set an increased mean temperature in the train compartment and measured the local equivalent temperature (T_{eq}) and local mean vote (LMV) per body-segment on a selected seat. This seat was equipped with an additional six-air-nozzle device attached to the backrest of the front seat. The objective comfort revealed the achievable ranges for the different settings as well as a strong local effect of the single air jets. The different configurations were afterwards studied in terms of subjective comfort evaluations based on questionnaires and the individual settings of 40 subjects. The results confirmed the positive cooling effect of the air jets as thermal comfort was significantly improved when the subjects used the six-air-nozzle. Air draughts at the subjects' upper legs and the temperature at their chest and face were most relevant for comfort sensations. Furthermore, the findings highlighted the highly subjective demand on the thermal environment as no two subjects chose the same nozzle configuration.

1. Introduction

Rail passenger transport must become more attractive to achieve the desired shift of passenger transport from road to other, more energy-efficient modes as defined by the EU [1]. Besides increasing the general attractiveness of rail transport, the efficiency of existing air-conditioning systems must be improved in order to reduce the overall energy requirements. In the present study, we focus on the air-conditioning system, which is the second largest energy consumer during a train journey, accounting for up to 30% of the total energy demand [2].

Nowadays, the ventilation of train compartments is optimized to provide overall comfortable conditions in the whole passenger area, neither addressing whether the seats are occupied nor taking the individual demands of the passengers into account. The existing standards clearly define the required air and surface temperatures, maximal air velocities and required fresh airflow rates [3,4]. Demand-controlled adjustment of the fresh airflow rate based on the CO_2 levels in the compartment is already well-established in order to save energy at low occupancy levels. However, comfortable conditions are still maintained for the entire compartment. New concepts are based on the idea of providing comfortable conditions only on occupied seats by generating localized climate zones. These new concepts offer great potential to save energy as the conditioning effort for the whole compartment is reduced and the individual subjective demands in terms of comfort can be addressed. In previous studies we presented infrared and seat heating elements to increase the individual equivalent temperature [5–8]. However, the concept of additional infrared and seat heating is only applicable under winter conditions. For summer conditions additional cooling would be needed, if the mean temperature in the compartment was to be maintained at increased levels to reduce the energy demand of the HVAC system.

For buildings, such as large office spaces, the concept of personalized environmental control systems (PECS) has already been discussed for decades, see e.g., the review article of Warthmann et al. [9]. Both scientific test environments [10–14] and fully equipped experimental [15] and simulated [16] offices were investigated. The main drawbacks can be summarized as the need for additional air vents and electric wiring as

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well as the complexity of some concepts regarding installation, control and maintenance. However, the studies also identified many advantages, such as decreased energy demand, improved acceptability of perceived air quality, positive effect of having personalized control of the temperature, improved thermal sensation, increased productivity and decreased downtimes due to sick-leave. Unfortunately, the findings of these studies cannot simply be transferred to vehicle cabins or railway compartments. In these cabins and compartments inhomogeneous and transient indoor climate conditions are common which do not correspond to the conditions in buildings (see also Lin et al. [17]).

In transport modes, full individual control of the local thermal conditions in terms of a PECS is only available in passenger cars, private jets or – to some extent – in first-class areas of passenger aircraft. What these cabins have in common is that the PECS is only provided for a rather small number of passengers. In passenger cars, personalized multi-zone thermal comfort areas are state-of-the-art. These provide individually controllable conditions at least for the driver and the co-driver, often also for the other passengers. Supply air temperatures and the direction of the air vents can be chosen individually. Occasionally, these ventilation systems are also supported by individual seat-heating systems. New technologies are constantly being developed and under research: Fojtlín et al. analyzed the benefit of installing individual sensors for equivalent temperatures in vehicle cabins [18]. 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 integrate personalized air conditioning in vehicles. They combined contactless thermal comfort measurements and simulated real-time data to provide thermally comfortable conditions via infrared heating panels and individual fans [19]. Despite the higher complexity of these sub-systems of the HVAC system, the advantages of addressing the individual, personal demands of the passengers in addition to considerable energy saving potentials (by direct and zonal heating and cooling) predominate.

In passenger aircraft, individual air nozzles – the so-called gasper nozzles – are state-of-the-art and investigated in many studies. Du et al. [20], for example, investigated the optimal velocity configurations for gasper nozzles in aircraft at different temperature levels. Their results confirm that at normal pressure, an airflow rate of 0–0.86 l/s at 24 °C, 0.12–1.09 l/s at 26 °C and 0.26–1.30 l/s at 28 °C for a nozzle is adequate/appropriate to maintain passenger thermal comfort, with both thermal sensation (TSV) and air movement sensation (AMSV) ranging from -0.5 to +0.5. The scale of TSV ranged from -3 “cold” to +3 “hot” and the scale of AMSV ranged from -3 “too weak” to +3 “too strong”. Further technical developments aim at adjusting the climate conditions in the aircraft cabin to better meet the passengers’ needs. You et al., for example, analyzed the thermal comfort provided by personalized displacement ventilation and compared it with mixing and conventional displacement ventilation systems using CFD simulations [21,22]. They found that personalized ventilation generated the best cabin comfort and reduced the risk of possible infections.

Although aircraft and (long-distance) trains have a lot in common, there are also important differences – especially when it comes to the main ventilation concept. Passenger aircraft cabins are all ventilated by a high-momentum air supply below and above the overhead luggage compartments. These air jets are typically oriented towards the aisle and establish the so-called mixing ventilation. In many long-distance trains, e.g., the German ICE, small micro jets coming from a trickle ceiling above the aisle supply the fresh air. Hence, a ventilation-based PECS will interact differently with the main ventilation system installed in typical aircraft or trains. Furthermore, the different air velocity fields combined with the different boundary conditions, both wall temperatures and interior configurations, result in different local (equivalent or operative) temperature distributions. Thus, the demand on additional cooling using the PECS might vary for the individual body parts in different transport modes. For train compartments, however, the literature on personalized comfort and especially air nozzles is scarce. Liu et al. [23], for example, investigated the impact of individual air nozzles in the arm rests on particle spreading in the train compartment. Their results revealed a reduction of approx. 25% in particle concentration in the breathing zone of the passengers. To our best knowledge, however, the application of individually controllable air nozzles in passenger trains has not been tested yet.

The present study deals with the application of individually controllable air nozzles in a train compartment operated at different volume flow rates and an increased mean temperature in the compartment. It focusses on the following research questions:

- Which local airflow rates of the PECS’s different air nozzles are chosen by the subjects? Are there preferred settings or settings which are not used?
- Which range of equivalent temperatures needs to be available to address the demands of the test persons?
- What is the subjective thermal comfort evaluation of the installed PECS for an increased mean temperature in the compartment?
- What effect does the individual vs. automatic control of the PECS have?
- Which correlations can be found between chosen settings, individual comfort evaluation and objective measures such as local mean vote?

To answer these questions, both subject tests and objective comfort evaluations were performed in a generic train laboratory located at the German Aerospace Center (DLR) in Göttingen.

2. Test facility and experimental setup

2.1. Generic train laboratory

The study was conducted in a generic laboratory, representing the lower cabin of the DLR’s next generation train (NGT), see Fig. 1. The inner dimensions of the compartment are $6.0 \times 2.88 \times 1.95$ m^3 (length x width x height) and it is equipped with 24 seats. During most investigations, thermal manikins are used to simulate the blockage and heat release of real passengers. These thermal manikins mainly consist of a foam core carefully wrapped with heating wire in precisely spacing. Each manikin is operated by a computer-controlled power supply ensuring a constant heat release rate of approx. 85 W during our measurements. The spatial distance of the heating wire is reduced at the heads, resulting in increased heat release rates and surface temperatures for this body part, that correspond well to human passengers. More detailed information on the thermal manikins, including their dimensions and operational modes can be found in [24,25].

The generic train laboratory features a stationary high-precision heating/ventilation/air-conditioning (HVAC) system, which guarantees well-defined and precise supply air conditions with temperature and airflow rate fluctuations as low as 0.1 K and 10 l/s, respectively. The latter corresponds to an accuracy of approximately 4.3% with regard to the absolute supply air volume flow rate of 230 l/s.

In previous investigations in the generic train laboratory, we analyzed different ventilation concepts in terms of objective and subjective thermal comfort [26,27], individual infrared (IR) heating elements [5] and aerosol spreading [28].

2.2. Multi-jet air nozzle

The PECS in our study is a multi-jet air nozzle system allowing for the ventilation of six different zones in the first step. It consists of six adjustable air vents embedded in a 3D printed housing and can be used to influence the following six main zones: head, chest, right and left arm/hand as well as right and left leg/foot. The zones for the two arms and the two legs are combined. Thus, four different zones can be controlled by the subjects in the current configuration. With a view to

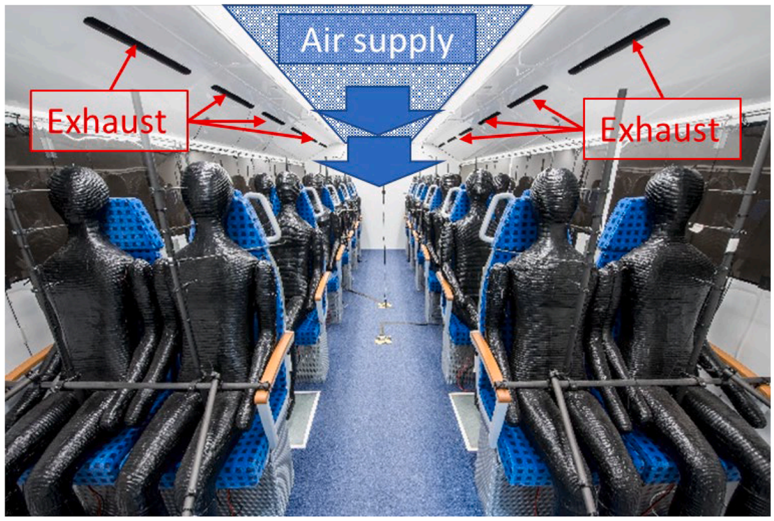

Fig. 1. View into the generic train laboratory fully equipped with thermal manikins © DLR.

retrofitting, the system was developed as a seat attachment for our existing laboratory seats. In a later step it might be designed as an integral part of future seat generations. The individual diffusers can be adjusted in terms of flow rate and direction. Fig. 2 shows a photograph of the system. P.193 round adjustable air diffusors with an open airflow section of 80 mm^2 from Prima industries were used as single nozzles, (see also schematic drawing in Fig. 2, bottom left). The system is installed on the seat in front of the evaluating passenger and the six

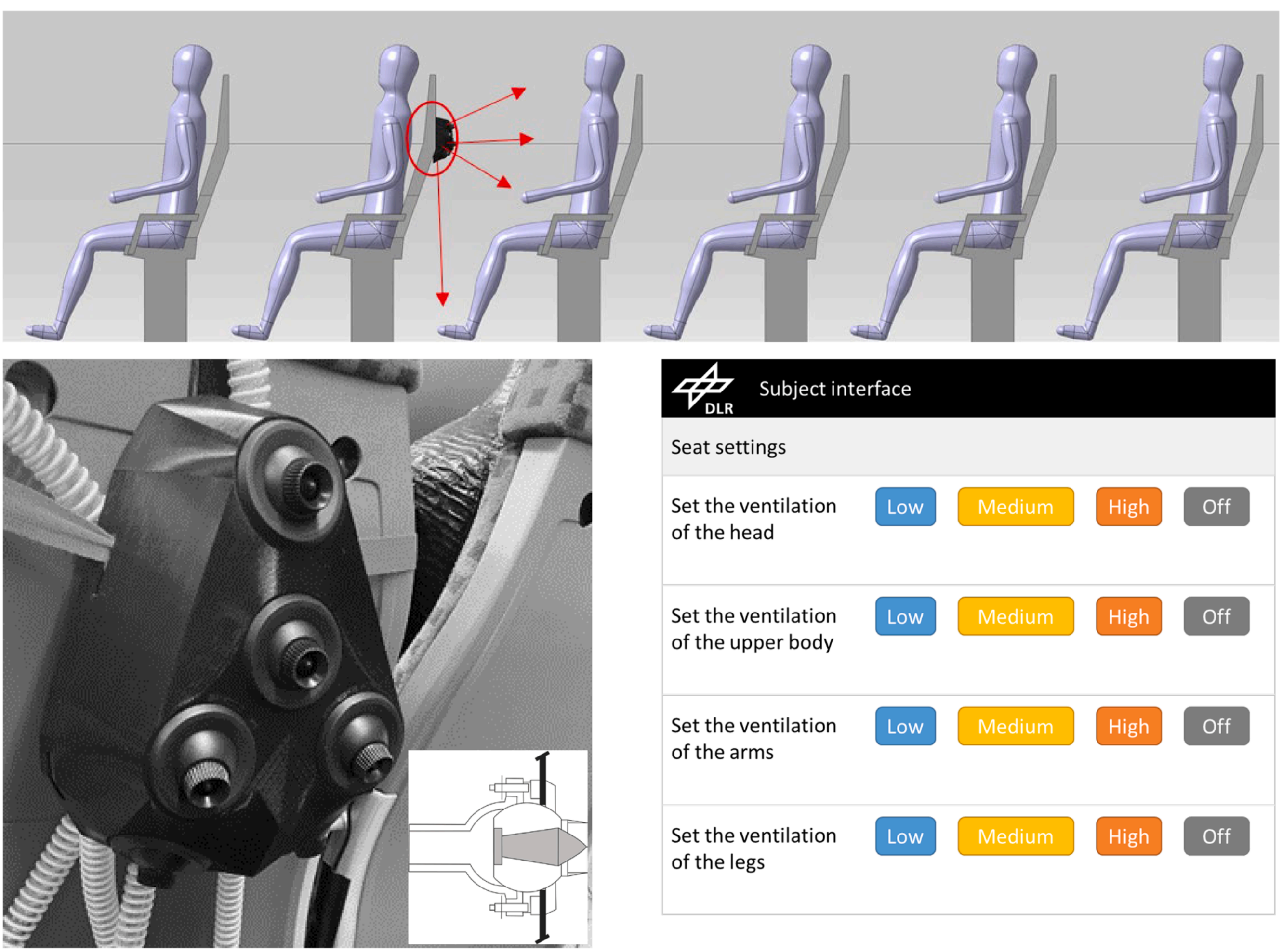

Fig. 2. Position of the PECS in the generic train laboratory, oriented towards the right aisle seat in the third row (top). Illustration of the personal multi-jet air nozzle with integrated schematic drawing of a single nozzle (bottom left). Layout of the control interface used during the subject tests (bottom right) © DLR., Note: German version of the layout was used during the subject tests.

adjustable air vents can be seen. In addition, six pipes – coming from the PECS – serve as air supply lines. These pipes are equipped with individual electric heating elements to allow for an individual adjustment of the air temperatures of the single jets in the range of approx. 20 °C to 60 °C with a temporal stability better than 0.5 K to 2.5 K, respectively, i.e., better than 5% (standard deviation). Furthermore, the pipes are connected to a mobile HVAC unit, which supplies pre-conditioned fresh air for all nozzles. Please note that the PECS was operated at a constant temperature during the subject tests. Pre-tests showed that different airflow rates outbalance different supply air temperatures regarding the effect on the objectively measured equivalent temperatures [29]. Integrated volume flow rate sensors (Sensirion SFM3000 sensors; accuracy: 2.5% of measured value) in combination with control valves in each pipe ensure a controllable and well-defined airflow rate in each nozzle. The system can generate flow rates between 10 l/min and 50 l/min per nozzle, see Table 1. The chosen flow rates were maintained with an accuracy better than 1.3 l/min (standard deviation). The resulting flow velocities and turbulence intensities are summarized in Table 2. The single air jet volume flow rates can be controlled both centrally from the test control center or via a mobile device, e.g., a smartphone or a tablet computer (Fig. 2, right), directly by the passenger in front of the multi-jet air -nozzle. The realignment of the nozzles or the manual adjustment of the flow rate by turning the nozzle head was restricted during the tests to allow for comparability.

It is noteworthy that the multi-jet air nozzle system - as presented above - cannot be directly implemented into standard rail vehicles. Nevertheless, this study sheds initial light on the important questions whether such nozzles are used in general and, if so, how. It provides insights into their potential positive effects on specific body parts and overall comfort evaluations. Thus, these results might enable future adaptations that could be integrated in standard rail vehicles.

3. Measurement techniques and test matrix

3.1. Boundary conditions

For the acquisition of the volume flow rates, air temperatures and humidity, the mobile measurement system of the DLR was used [30]. Sensirion SHT85 and SFM3000 probes were installed to ensure an accuracy of 0.2 K (temperature), 1.5% rh (humidity) and 1.5% of the measured value (volume flow rate). It should be noted that the mean temperature in the compartment T_{im} is calculated by four temperature probes at a height of 1.10 m arranged diagonally in the laboratory, in accordance with EN13129 [3]. The humidity was recorded but not actively controlled during the measurements, neither in the PECS nor in the main ventilation system.

3.2. Velocity field measurement

The 3D velocity field generated by the multi-jet air nozzle was measured using an optically tracked three-component ultrasonic anemometer (Streamwise Procab). This measurement system allows for a non-time-resolved acquisition of all three velocity components and the fluid temperature in a pre-defined three-dimensional measurement volume. In the current study, the measurement volume is represented by a cubical box with a side length of 800 mm reaching from the multi-jet air nozzle to the ventilated thermal passenger manikin. The spatial resolution was set to 2 cm and the accuracy of the velocity probes is given as 0.1 m/s with a resolution of 0.01 m/s.

Table 1
Setpoint values of the subjects.

Setting Flow rate $\dot{V}$ $[l/min]$	Off	Low	Medium	High
Head	0	10	30	50
Upper body/chest	0	10	30	50
Arms/upper legs*	0	20	60	100
Lower legs/feet*	0	20	60	100

Note:
*two nozzles: flow rate per nozzle is half of given value.

3.3. Equivalent temperature (equites system)

The thermal comfort in terms of the individual body segments was assessed using Comlogo's equites sensor system [31]. It consists of 16 probes acquiring the equivalent temperature stipulated in EN 14505-2 [32]. Thus, the objective thermal comfort can be recorded and evaluated in accordance with international standards and well-accepted comfort levels ranging from too cold via cool, neutral, slightly warm to too warm. It should be noted that it is distinguished between summer and winter conditions as the thermal comfort evaluation of similar equivalent temperatures differs, see EN14505-2 [32]. The installation of the Equites sensors on a manikin seated in front of the multi-jet air nozzle is depicted in Fig. 3.

3.4. Subject tests

Human subject tests were performed in autumn 2023 in the generic train laboratory in order to assess potential passenger comfort and demands.

3.4.1. Measures

Subjective data were assessed using standardized rating techniques. Questionnaire items, see also Table 7 in the appendix, were electronically assessed via tablets: The participants rated the sensation and comfort of two indoor climate parameters – air temperature and air velocity. The intensity of the climate sensation was rated on seven-point scales (temperature: 1 = very cold, 4 = neutral, 7 = hot; air draught: 1 = not at all, 4 = neutral, 7 = very strong). In addition, the subjects estimated the indoor temperature in degrees Celsius. The comfort assessments for temperature and air velocity were collected locally with reference to different body parts (face, chest, hands, upper legs, feet,) and globally for the whole train compartment. The comfort aspect of each climate parameter was evaluated using a five-point rating scale ranging from 1 = very uncomfortable, 3 = neutral to 5 = very comfortable. Furthermore, a general indoor climate satisfaction judgment was given on a five-point rating scale ranging from 1 = very dissatisfied, to 5 = very satisfied. Finally, the participants were asked to indicate their physiological well-being in terms of coziness. This scale was derived from the 'Questionnaire for the assessment of current physiological well-being' [33]. The scale was composed of 7 items which were graded on a five-point scale (1 = not at all, 3 = more or less, 5 = completely). Item examples are: "I feel comfortably warm" and "I have a pleasant feeling on my skin". The climate satisfaction judgment and the coziness evaluations were averaged to form an overall comfort rating. We refer to this overall judgment as "climate comfort".

3.4.2. Sample

The participants were recruited via an online job platform of the University of Göttingen. In total, 40 subjects participated in the test trials carried out on four days. The optimal sample size for group comparisons to detect large to medium effects is between 15 and 34 for the paired samples *t*-test and between 26 and 64 for the unpaired samples *t*-test, so that the chosen N = 40 was appropriate for the research questions [34]. The study was conducted in accordance with the model code of ethics of the European Federation of Psychologists' Associations (https://www.efpa.eu/model-code-ethics). The test persons were informed about the content and the course of the experiment in a detailed presentation before the start. They were assured that their data will be evaluated anonymously and they confirmed their voluntary participation in a test subject contract.

Nearly half the subjects were female ($N = 21$), half were male ($N =$

Table 2
Summary of the boundary conditions.

	Temperature	Flow rate	Air velocity	Turbulence Intensity	Humidity
Main ventilation supply air	T_{in} = 20.0 °C	230 l/s (i.e., 828 m^3/h)	≈ 3.8 m/s[§] ≈ 0.34 m/s[#]	23 %[#]	≈ 50 % rh
Mean within compartment	T_{im} = 27.0 °C	—	0.16 m/s[+]	—	34–39 % rh
Mean inner walls	T_{walls} = 27.3 °C	—	—	—	—
PECS	T_{supply} = 26.5 °C	10–50 l/min[*] (i.e., 0.6 -3 m^3/h)[*]	0.8–3.7 m/s[$]	42–27 %[$]	35 % rh
Ambient conditions	≈ 20 °C	—	< 0.3 m/s	—	≈ 50 % rh

Note:
[*] value per nozzle given.
[+] averaged over four heights in the vicinity of seated manikins in row 03, see also [26].
[§] calculated using the effective nozzle area of the micro jet ventilation elements and the total volume flow rate, see also [26].
[#] measured 10 cm below the air supply elements in the ceiling.
[$] measured 10 cm in front of the nozzle.

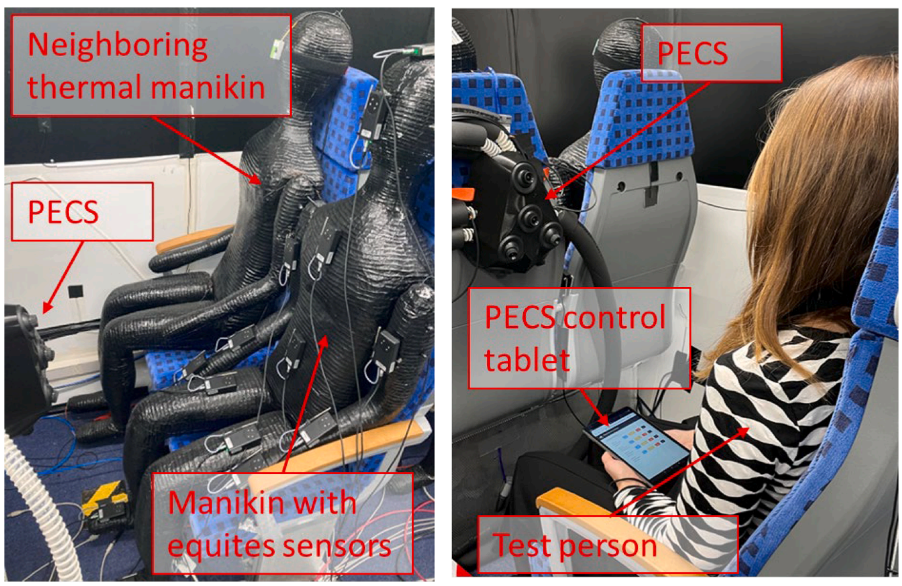

Fig. 3. PECS installed on the seat in front of the evaluating passenger with direction of influence on a thermal human model with 16 equivalent temperature comfort sensors (left). Photographs taken during the subject tests (right). © DLR.

18) and one subject was without information. The subjects' age ranged from 19 to 44 years (M = 24.3, SD = 4.5), their height was between 158 cm and 202 cm (M = 176.1, SD = 9.9), and their mean body mass index (BMI) ranged from 19.2 to 38.6 (M = 23.3, SD = 3.8). In order to ensure equivalent clothing conditions (≙ 0.7 clo), all participants were advised to wear thin shirts with long sleeves, long trousers and low-top shoes. Scarfs were not allowed. For their participation, the subjects were compensated monetarily.

3.5. Procedure and test matrix

On each of the four days, ten subjects participated in the experiment consecutively. In each trial the same procedure was applied: The participants were welcomed in the laboratory hall, where they stayed in constant environmental conditions for 20 min and received a short presentation on the content and the course of the experiment. In addition, they got a short introduction regarding the handling of the survey tablets. The test subjects were informed that all their data will be evaluated anonymously and they confirmed their voluntary participation in a test subject contract. After that, the participants were accompanied to their seats in the mockup and received some further instructions concerning the handling of the control interface for setting the air nozzles before the start of the experiment. During the experimental phases, the subjects remained seated. All other seats in the mock up were occupied by thermal manikins. The environmental conditions during the experimental phases were kept constant on all experimental days.

Three consecutive experimental phases, i.e., different conditions, were implemented: t_i = individual control of air nozzles, t_0 = baseline scenario without air nozzles and t_a = automated control of air nozzles. The phases t_i and t_a differed in terms of the individual control possibility. In phase t_i, the temperature was set by personal control. The individual setting of the air nozzles which the subjects had chosen during the experimental condition t_i was restored and used for condition t_a without the subjects being aware of this. Thus, in phase t_a, the temperature was set without personal control but with an automated control.

Each phase (see Fig. 4) lasted 20 minutes. In the first 15 minutes of the exposure time, the subjects could choose between two different kinds of entertainment (option 1: solving crosswords or Sudoku grids; option 2: reading a "neutral" magazine). Additionally, they could change the setting of the air nozzles in the condition with individual control (t_i). After 15 minutes, the individual temperature control was disabled and the final individual settings were recorded. These settings were applied again in the automatic control phase (t_a). During the last 5 minutes of the exposure time, the subjects filled out the comfort questionnaire while the climate remained unchanged.

After all subject tests were completed, another measurement campaign was performed to assess the objective thermal comfort of the subjects' parameter choices. For this purpose, the generic train laboratory was operated at the same settings as during the subject test, only the seat in front of the PECS was occupied by a manikin equipped with

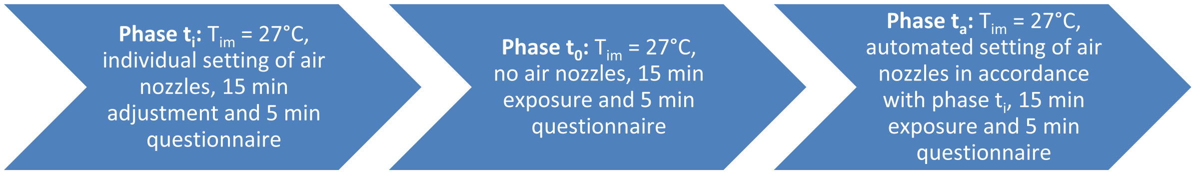

Fig. 4. Experimental phases.

Equites equivalent temperature sensors instead of the human subjects. All other seats were occupied by thermal manikins. Consecutively, the individual settings of the 40 subjects, out of 256 different combination possibilities, were reproduced and local equivalent temperatures were recorded per body segment. For each parameter combination, a sufficiently long settling time was chosen to ensure well-converged results.

4. Results

4.1. Airflow pattern of multi-jet air nozzle

Fig. 5 shows different representations of the velocity field between the multi-jet air nozzle and the thermal manikin obtained using the 3D velocity measurement technique. The volume flow of each single nozzle was adjusted to 50 l/min, i.e., the setting “high”. The cross section, shown in (a), reflects the vertical central plane in front of the manikin, i.e., it is aligned with the two nozzles aiming at the head and the upper body. There are two main findings: firstly, two high-velocity air jets are generated by the two nozzles in this plane. Secondly, the jets rather reach the chest and the lower stomach than the aimed head and chest region. In the jets, local velocities of up to 1 m/s can be found in the core region all the way to the passenger. The jets’ width is in the range of 10 cm highlighting the local orientation. The air jets of the other nozzles for the legs and arms are not visible in the cross section since they are not located in the central cross section of the multi-jet air-nozzle.

Additionally, Fig. 5 (b) represents the three-dimensional iso-surfaces of the velocity magnitude – colour-coded for three magnitude values: 0.3, 0.5 and 0.7 m/s. Parts of the jet towards the passenger’s left arm are visible next to the two jets towards the chest and the lower stomach. Again, it is confirmed that the single jets can be used to influence the local air velocity at different body parts of the seated passenger and thus, direct effects on the local equivalent temperature, i.e., the local thermal comfort, are expected and will be addressed in the next sections.

4.2. Parameter settings of the subjects

In phase t_i of the human subject test, the subjects had the opportunity to adjust the airflow rate of the individual nozzles to their needs. The default setting for all nozzles was "medium". In the following, the selected settings will be discussed in order to find out whether the volume flows of the individual nozzles (Table 1) were well chosen or should be changed in one direction or the other. A predominant use of the setting options “low” and “medium” would indicate a satisfactory airflow range. Frequent use of the highest level "high" could mean that the airflow was not sufficient. If the nozzles were not used at all, they were either not necessary or the draught was too strong even at the lowest level.

As recorded during the subject tests, all settings of the four nozzles were used, they were only rarely switched off (Table 3). The nozzle that was used the least was the nozzle for the head, which was switched off six times and set to "low" 15 times. The nozzle for the upper body/chest was most frequently set to the maximum setting “high”. In order to determine the extent to which the option of adjusting the nozzle on the upper body was sufficient for the subjects, the climate satisfaction of subjects with different settings was analyzed with an unpaired *t*-test. It turned out that the subject group who had set the nozzle aiming at the upper body to "high" was still more dissatisfied with the climate (climate satisfaction = 2.8, N = 17) than the remaining 22 subjects (climate satisfaction = 3.4), $t(37) = -1.75$, $p = .04$, one-sided test. This indicates that the volume flow for the upper body could have been slightly higher in order to achieve even higher satisfaction. The corresponding comparison for the nozzle aiming at the arms/upper legs showed similar results. The climate satisfaction was 3.0 for the group that had chosen the setting “high” (N = 15) vs. 3.25 for the remaining group (N = 24). However, this difference was not significant, $t(37) = -0.71$, $p = .24$, one-sided test.

4.3. Objective thermal comfort

4.3.1. Pre-tests

The objective thermal comfort in terms of the equivalent temperature was recorded prior to the subject tests for four different settings: “off”, “low”, “medium” and “high”. For a single case, all nozzles were

Table 3
Nozzle settings of the subjects, absolute values (N = 40).

	Off	Low	Medium	High
Head	6	15	13	6
Upper body/chest	3	8	12	17
Arms/upper legs	4	6	14	16
Lower legs/feet	6	4	16	14

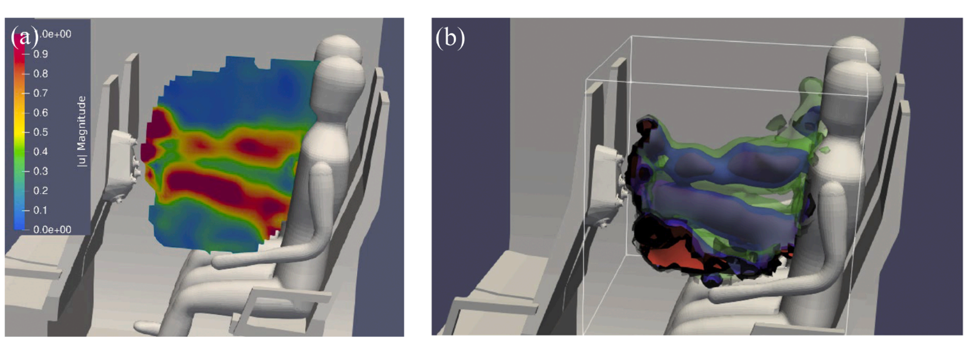

Fig. 5. (a) Velocity magnitude in the vertical central cross section on the manikin (b) Exemplary iso-surfaces of the velocity magnitude at $|U| = 0.3m/s$ (green), $|U| = 0.5m/s$ (blue) and $|U| = 0.7m/s$ (red) of the resulting 3D velocity field generated by the multi-jet air nozzle at iso-thermal air supply.

operated at the same volume flow rate and the mean temperature in the compartment as well as the supply air temperature of the nozzles were maintained at $T_{im} = 27\ ^{\circ}C$ and $T_{nozzle} \approx 26.5\ ^{\circ}C$. Fig. 6 represents the results of this pre-measurement for the different body parts. The background color of the diagram follows the comfort levels from too cold via neutral to too warm in accordance with EN ISO 14505-2 [32]. For the case without additional ventilation of the PECS (blue markers), we recorded warm but comfortable temperatures for the upper part of the body (02 - 10) and slightly too warm temperatures for the lower part of the body (11 - 16). Exceptions are the head (01; note: blue marker is hidden behind the red marker) which is also warm and the left foot (15; note: blue marker is hidden behind the green marker) which is assessed as neutral. The latter is assumed to be caused by the seating position on the right side of the aisle, i.e., the left foot of the manikin is in the aisle region and might be influenced by air movements, which are downward oriented in the aisle, see also measurements in Schmeling et al. [26]. Setting the PECS on "low" for all nozzles — shown as red markers – does not change the objective thermal comfort significantly compared to the off-configuration. Due to the absence of a cooling effect by the air movement, we conclude that the additional airflows, generated by the multi-jet air nozzle, do not reach the passenger when set to "low".

For higher flow rates of the PECS, i.e., "medium" setting (green) or "high" setting (purple), strongly decreased equivalent temperatures were recorded for selected body parts. For most of the body parts, the lowest equivalent temperatures occurred for the highest airflow rates. However, for the face, the strongest cooling effect was recorded for the setting "medium" of the PECS. This local effect is probably caused by the different propagation paths of the additional airflows. We assume that one air jet directly reaches the face in case of the "medium" setting, while for the highest flow rates this jet reaches another body part. This finding, even though it is a single effect, highlights the challenges when it comes to designing air jets which are supposed to influence single body parts: not only the orientation of the nozzle but also the airflow rate and possibly also the setting of the other nozzles as well as the interaction with the thermally and pressure-driven airflows in the whole compartment influence the area where the jets reaches the sitting passenger.

At the highest flow rate of the PECS, reductions of the local equivalent temperature of up to 9 K were achieved. These result in equivalent temperatures which are already evaluated as slightly too cold (chest (03+04), upper right arm (06) and upper legs (11–12)). Other body parts, e.g., hands (09+10) or feet (15+16), however, are only weakly influenced by the PECS. Hence, for the sitting position of our manikin, these body parts are not, or only weakly, reached by the air jets from the PECS.

In general, the pre-study confirmed that the chosen parameter range for the accessible air jet volume flow rates which were to be used for the subject tests allowed to generate significantly differing thermal conditions for most of the body parts. Hence, in accordance with the objective thermal comfort evaluation, the subjects should be able to determine their individual, intermediate settings to achieve the most comfortable conditions as long as they neither prefer very warm nor very cold conditions.

4.3.2. Post-tests

Following the test subject trials, all 40 individual settings of the test subjects were objectively measured again. As a result, we obtained the thermal comfort evaluations for the single body parts for each single subject. Fig. 7 depicts these values as boxplots of the equivalent temperature for each body part. Median values of the 40 settings for the equivalent temperatures are shown as magenta lines, the box covers 50%, i.e., the inter quartile range (IQR), of the data points and the whiskers show the lower and upper thresholds of the data. Single outliers are shown as circles. The background colors of the plots represent the comfort ranges from too cold (dark blue) via neutral (green) to too warm (red). The first point to notice is the significant difference between the different body parts; some body parts showed only small variations between all subjects, e.g., head (01), upper chest (03) or upper right leg (12). Others showed very wide ranges, e.g., lower chest (04), left hand (09) or left calf (13). The large variations reflect that the subjects chose quite different settings for these body parts. Small variations of the equivalent temperature of single body parts (Fig. 7) might have two different causes: the subjects did not choose different settings for these body parts, and/or the orientation of PECS air jets did not reach these body parts. The latter explanation is supported by the fact that for some body parts, e.g., head (01), hands (09+10) or left foot (15), different nozzle settings did not influence the local equivalent temperature, see also Fig. 6. For these body parts, the local equivalent temperature changed only weakly for the different nozzle settings. Hence, some of the small variations in the objective comfort reflected in the subjects' settings are probably a result of the jet configuration. Others, however, (e.g., upper chest) must be caused by homogeneous settings of the subjects. The slightly too warm equivalent temperatures at head level (01) are ascribed to the limited cooling effect for this body part. It should be noted that the sensor for the head is installed above the head as compared to the face sensor, see also Fig. 3 (left), and therefore the small

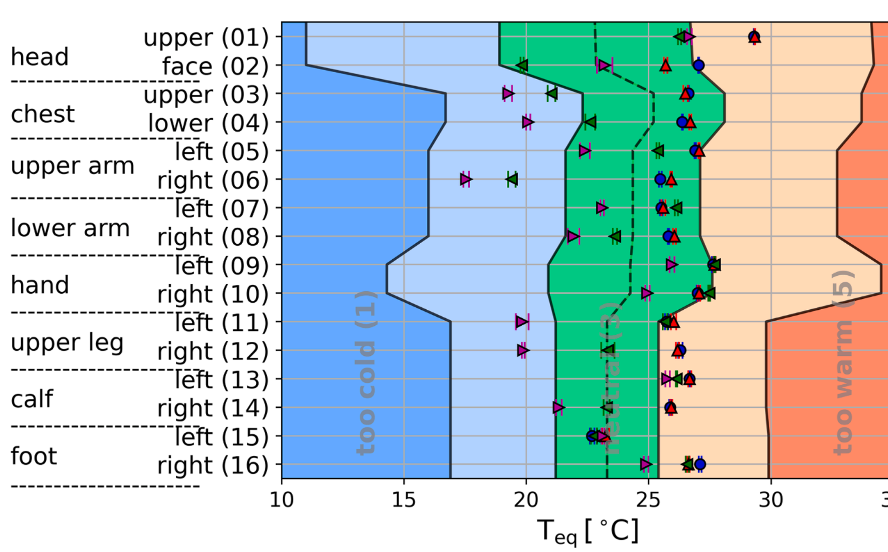

Fig. 6. Local equivalent temperatures for the different flow rates (all nozzles "off": blue, all nozzles "low": red, all nozzles "medium": green, all nozzles "high": purple) of the PECS.

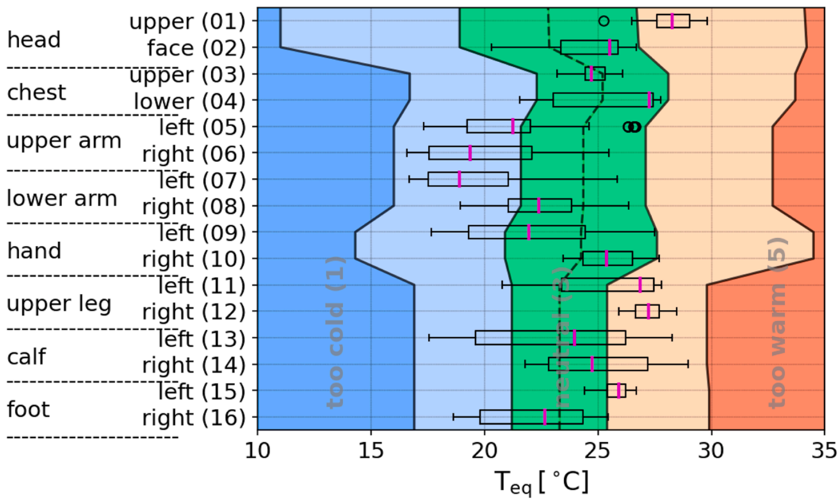

Fig. 7. Boxplots of the resulting objective equivalent temperatures for the different individual settings of the subjects.

effects on the jets at the head sensor position can be explained.

For the face and chest (02–04) all subject settings resulted in neutral, i.e., comfortable equivalent temperatures, neither too warm nor too cold. Much stronger variations, i.e., very different settings of the jets, were found for the arms (05–08), where variations of up to 10 K (whisker to whisker) were measured and most subjects chose slightly cooler conditions. For the lower body parts (11–15), higher equivalent temperatures were measured.

In general, we can conclude from the boxplots of the equivalent temperatures of the 40 subjects' settings that a) different temperatures are chosen for different body parts, b) the variation of the values depends on the body part and c) the 40 subjects have strongly individual demands reflected by variations as large as 11 K (whisker to whisker) or 6.5 K (IQR). The latter finding will be useful for the future design of PECS to determine the range of accessible equivalent temperatures required to satisfy the individual demands of the passengers.

Fig. 8 presents the local mean votes (LMV) of the subject settings. The range from −0.5 to +0.5 reflects the comfortable area. The LMVs were acquired with the Equites comfort probes. The presentation in terms of the boxplots is similar to Fig. 7: median values are shown as orange lines and 50% of the individual LMVs recorded for the 40 different settings of the subjects are within the box. The whiskers mark the lower and upper threshold of the recorded LMV and outliers are shown as additional circles. The following general trends and results can be found:

- Different body parts are evaluated very differently ranging from LMV ~ -1.5 up to ~ +1
- The range of the recorded LMV for the different subject settings shows strong deviations for the individual body parts: 50% range: Δ LMV as low as ~0.2 for the head and as high as 1.5 for the left calf, and full range: Δ LMV as low as ~0.45 for the head and as high as 2.5 for the left calf

4.4. Subjective comfort evaluation

In the following, the results of the comfort assessment during the human subject tests will be presented. The sensations and comfort evaluations of the climate parameters 'temperature' and 'air velocity' as well as 'climate comfort' were compared for the three test conditions, t_i: individual setting of the nozzle, t_0: no nozzle, t_a: automatic setting of the nozzle. Due to a technical error, one data file was corrupt and data sets of only 39 subjects were available for the analyses. Individual comparisons were carried out using paired samples *t*-tests. The comfort values for temperature, air velocity and the general indoor climate were higher for the two phases with a nozzle (t_i and t_a) than for the phase without nozzle (t_0, Table 4). The air draught was perceived to be stronger in t_i and t_a than in t_0. This means that the subjects successfully used the nozzle to improve their climate comfort compared to the condition without nozzle. The air temperature estimation in °C was consistent with the

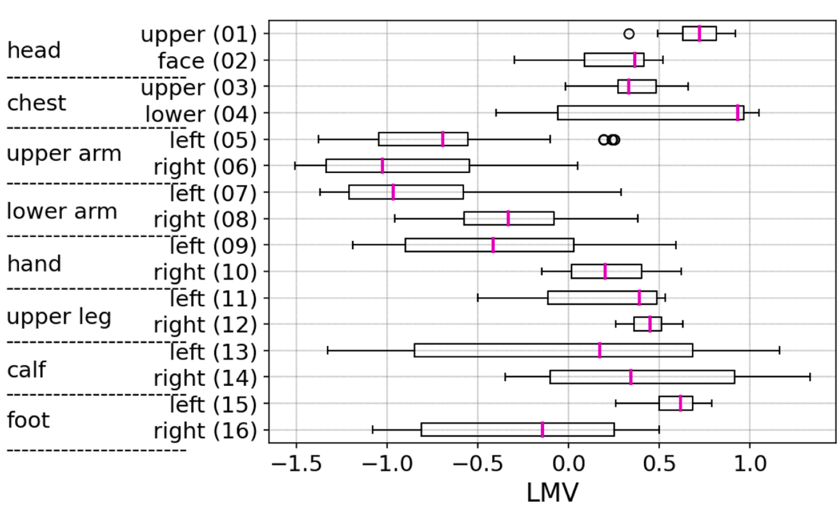

Fig. 8. Boxplots of the resulting objective local mean votes (LMV) for the different individual settings of the subjects.

Table 4
Sensation and comfort evaluation of temperature, air velocity and climate and test statistics of paired samples *t*-tests.

		t_i	t_0	t_a		t_i vs. t_0	t_i vs. t_a	t_0 vs. t_a
Temperature sensation	*M*	5.13	5.33	4.54	*p*	.17	**<0.001**	**<0.001**
(1 = *very cold* to 7 = *hot*)	*SD*	0.95	1.01	1.05	*t(38)*	-1.34	4.33	4.01
Air draught sensation	*M*	3.67	2.44	3.87	*p*	**<0.001**	.22	**<0.001**
(1 = *not at all* to 7 = *very strong*)	*SD*	1.28	1.25	1.34	*t(38)*	4.63	-1.24	-5.19
Temperature comfort evaluation	*M*	3.23	2.77	3.54	*p*	**.01**	.17	**<0.001**
(1 = *very uncomfortable* to 5 = *very comfortable*)	*SD*	1.33	1.31	1.17	*t(38)*	2.69	-1.41	-3.62
Air draught comfort evaluation	*M*	3.62	2.95	3.72	*p*	**.003**	.55	**.002**
(1 = *very uncomfortable* to 5 = *very comfortable*)	*SD*	0.91	1.10	0.92	*t(38)*	3.14	-0.60	-3.33
Air temperature estimation in °C	*M*	24.30	25.16	23.19	*p*	**.01**	**<0.001**	**<0.001**
	SD	3.97	4.90	3.75	*t(36)*	-2.81	3.84	4.68
Climate comfort	*M*	3.49	3.15	3.64	*p*	**.03**	.21	**.002**
(1 = very low to 5 = very high)	*SD*	0.78	0.86	0.74	*t(38)*	2.30	-1.28	-3.42

Note. Significant p-values < 0.05 in bold

sensations of temperature and air draught: t_0 was estimated to be the warmest with the lowest air draught, followed by t_i and t_a.

In order to take the subjects' thermal comfort per body part into account, the respective climate comfort evaluations for temperature and air draught are also depicted as boxplots (Fig. 9). Most boxes are above the (neutral) scale mean of 3, as expected from the measurement data shown in Fig. 8, where the majority of the values are on the "comfortable" side of the scale. Nevertheless, the ranges of comfort evaluations differed between the individual body parts with whiskers for the chest and feet area covering the whole scale range from 1, "very uncomfortable" to 5 = "very comfortable". Interestingly enough, the LMV data (Fig. 8) also reflect a comparatively larger variation of values for (lower) chest and feet.

We further investigated how the thermal sensation for different body parts influences the subjects' overall climate comfort. Linear regression models were used to determine the relationship between climate comfort evaluations for individual body parts and the overall climate comfort. The focus was on the impact of central body parts, namely, face, chest, upper legs, and feet. The dependent variable was the perceived climate comfort, which was predicted using comfort evaluations for these four body parts regarding perceived air draught and air temperature. Therefore, subjective ratings were aggregated over the two phases with nozzle ($t_i + t_a$) which increased the reliability of the data.

Significant regression models were obtained for both air draught and temperature variables (see Table 5). This means, it is possible to predict climate comfort by means of body-part-related air draught and temperature comfort, respectively. Regarding air draught, one predictor reached statistical significance: The air draught at the upper legs contributed significantly to the subjects' overall climate comfort. The regression weight was positive, indicating that the more agreeable the air movement at the upper legs was evaluated, the better the climate comfort was rated. Regarding the temperature comfort, two predictors

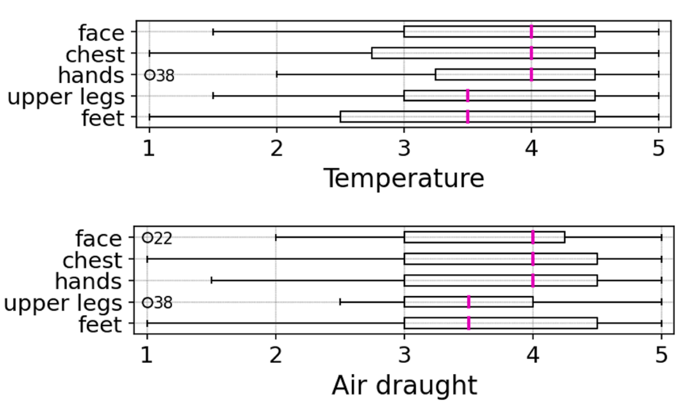

Fig. 9. Boxplots of the subjective climate comfort evaluations per body part, scale ranging from 1 = *very uncomfortable* to 5 = *very comfortable*.

Table 5
Prediction of subjects' climate comfort by body-part-related comfort evaluations using linear regression modelling.

DV	IV	*B*	*β*	*t*	*R*	*F*	R^2 (R^2corr.)
Air draught							
	Climate comfort	1.06		1.64	.62**	5.07	.38 (0.31)
	Face	.14	.20	1.40			
	Chest	-0.06	-0.06	-0.34			
	Upper legs	.59**	.61	3.14			
	Feet	.01	.01	.04			
Temperature							
	Climate comfort	1.23		3.08	.79**	13.58	.62 (0.58)
	Face	.20+	.25	1.96			
	Chest	.49**	.69	4.75			
	Upper legs	-0.06	-0.08	-0.54			
	Feet	.00	.00	-0.02			

Note.
** $p \leq .01$.
+ $p \leq 0.10$.

were statistically significant: the temperature comfort in the facial area ($p = 0.10$) and the temperature comfort at the chest. Both had positive regression weights, indicating positive relationships with the climate comfort rating. As reflected in the higher regression weight, the temperature comfort at the chest had a larger impact on the prediction than the comfort in the facial area.

In sum, it was found that the air draught at the subjects' upper legs and the temperature comfort at their upper body and in the facial area were relevant predictors for the subjects' climate comfort.

4.5. Relationship of subjective and objective comfort data

To correlate the subjective and objective evaluations, the subjective ratings were aggregated over the two phases with nozzle ($t_i + t_a$) and the objective data were summarized over 16 body parts. Neither the sensation nor the evaluation or estimation of the temperature showed any correlation with the equivalent temperature (see Table 6). The only correlation of objective and subjective data that approached significance was that of air draught sensation and equivalent temperature with $r = -0.27$; $p = 0.10$. This means that the stronger the draught was perceived, the lower the equivalent temperature was. The second highest correlation was found between climate comfort and equivalent temperature with $r = 0.26$, $p = .11$.

Despite these scarce correlations between the subjective ratings and the objective evaluations, the temperature sensation of the subjects was more or less in the same range as the equivalent temperature. Both average values ranged from 23 °C to 24.5 °C (Fig. 10), while the mean cabin temperature (T_{im}) was about 4 °C higher with an average of 27.9

Table 6
Bivariate correlations between subjects' ratings and objective comfort measurements.

	Objective evaluation
Subjective ratings	Equivalent temperature
Temperature sensation	- 0.05
Temperature comfort evaluation	.14
Air draught sensation	- 0.27+
Air draught comfort evaluation	- 0.13
Air temperature estimation in °C	-0.03
Climate comfort	.26

Note: + $p < .10$; N = 39, subjective ratings = mean (ti, ta); objective evaluations = mean of 16 body parts.

°C. This indicates that the equivalent temperature determined by 16 sensors predicted the *average* thermal perception of the subjects quite well. However, there was a variation among the individual temperature measures for the test subjects, which could not be captured by the equivalent temperature. Across the two phases with nozzle (t_i + t_a), subjective air temperature estimations had a range of 28 °C. As illustrated in Fig. 10, the equivalent temperatures had a range of 5.3 °C and the USB-Logger measurements had a range of only 2 °C. Obviously, two extreme cases contributed substantially to the broad range of subjective ratings, namely subjects #11 and #31. Both were male subjects with no further indication regarding extreme sensations.

5. Discussion

In the following sub-sections, we will discuss the limitations of the study, the transferability of the results to other train geometries, the impact on train operation and the subjective data.

5.1. Limitations of the study

Firstly, it should be noted that the installed prototype of the multi-jet air nozzle did not allow for a change of the orientation of the nozzles, i. e., the flow direction of the individual jets could not be changed to address individual demands. Furthermore, the installed PECS excluded e.g., overhead nozzles and therefore the presented results cannot be used for a final design of the "best" nozzle configuration in a train compartment. Consequently, the presented study is rather a generic laboratory test than a design optimization study.

Secondly, the study was performed in the generic train geometry with different boundary conditions and dimensions compared to trains in operational mode. We are fully aware of the generic setup of the study and the fact that real operational conditions are different. Therefore, a detailed optimization process for the locations and adopted volume flow rates of the nozzles is required for any real train compartment. However, the conditions in the generic train laboratory are well-balanced between reality, e.g., train seats and ventilation concept, and simplifications by well-defined boundary conditions, e.g., sidewalls or using thermal manikins to simulate other passengers.

Thirdly, only steady or quasi-steady configurations were investigated in the present study. We assume that this limitation does not affect the results for long-distance travel, e.g., in business class, where the train only rarely stops and the change in the interior configuration, e.g., moving passengers is small. In regional trains with many stops and more crowded compartments, the difference between steady-state and real conditions might be more significant. In upcoming studies, transient conditions should also be investigated, e.g., changing the mean temperature in the compartment or allowing the passengers to readjust the air nozzle over a longer period of time to consider their changing activity and metabolic rate. Especially the latter could be of high interest due to the different travelling times of the passengers in the same train and consequently the different demands in terms of the local thermal environment.

Fourthly, the objective equivalent temperature was measured locally using sensor elements which have an active surface of about 5 cm^2. Air jets not directly reaching a sensor element are not detected. Accordingly, some air jets might reach, e.g., the upper arm and thus reduce the subjects' perceived temperature, but have no influence on the objective comfort of the local, sensor-based measurement of the equivalent temperature. The application of a full thermal comfort manikin, which enables a surface-averaged evaluation of local temperatures and heat fluxes per body segment could be helpful in future studies.

Finally, though subjects stayed in constant conditions in our laboratory hall at approx. 20 °C before the start of the experiment, due to timely restrictions, it was not possible to realize a longer adaptation phase to the experimental temperature setting (27 °C). Seen from a neurological perspective, thermal and mechano-receptors react to temperature or pressure changes in seconds, and then only take a few minutes to adapt to a certain temperature or air movement. Consequently, humans can sense thermal conditions immediately. In our experimental setting, subjects had an exposition time of 15 to 20 min to each condition before they answered the questionnaire for the respective scenario. From our experience, this period is well-suited for adapting to new climate conditions and for making reliable and valid thermal comfort judgments in thermal environments. This is also reflected in research addressing transient thermal environments, where assessments in changing temperature conditions usually take place every 5 to 10 min (e.g. [35,36]).

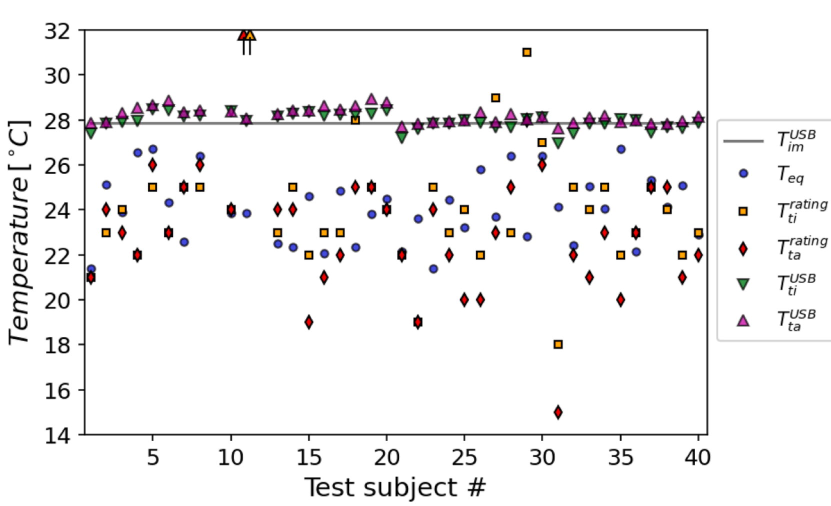

Fig. 10. Temperature measures per test subject.

5.2. Transferability to other train compartments

Although our study is based on a generic setting (see Section 5.1), the design of both, nozzles and investigated compartment, ensures that the results are not biased by a specific geometry and thus are – in general – transferable to other train geometries with the mentioned design optimizations. The key factor will be the final location of the nozzles, i.e., the distance to the passengers and their orientation. The most challenging configurations, where the present results will only have limited applicability, are face-to-face seating arrangements, e.g., with a table. In this case an installation of the nozzles in the backrest of the seat in front is not feasible and alternative positions, e.g., in the sidewalls or the hat racks are needed.

5.3. Impact on train operation

The implications of personal, individually controllable air nozzles in passenger trains are multiple and differ depending on the installed control elements. First of all, the set-point curves of the main HVAC unit should be adopted to take the changed mean temperature in the compartment into account. That means, a higher temperature should be defined as set-point during cooling mode. If the personal air nozzles are to be controlled via an app, e.g., QR codes will be required to guide the passenger to the respected control page. This could be integrated into the ticket app and could also be connected to the seat reservation system or the contactless ticket control, both already established in, e.g., the DB Navigator app [37]. Such a system would also facilitate an automatic pre-control of the individual nozzles based on the preferred setting of the passenger which could be stored in the app. However, such a control system would exclude passengers without smart device from adjusting their individual ventilation and possibly reduce the thermal comfort for these travelers. An alternative control system could be based on a seat-integrated control panel, e.g., touch screen, push or turn buttons.

5.4. Discussion of subjective data

The nozzles have effectively created a more comfortable climate for most of the subjects. The air movement was perceived as pleasant and the resulting temperature was perceived as cooler and more comfortable than in the scenario without nozzles. It made hardly any difference whether the nozzles were set by the passengers themselves or whether their saved settings were used for an automatic setting which is in line with former findings [8,38,39].

The specified flow rates of 10 to 50 l/min for ventilating the head and 20 to 100 l/min for the arms and legs gave the test subjects sufficient opportunity to set their personal airflow. Only the maximum flow rate of 50 l/min for the upper body was too low, as many subjects chose the maximum and were still dissatisfied. A maximum flow rate higher than 50 l/min is recommended for the upper body.

In general, the subjects estimated the room temperature to be approx. 4 °C lower than it actually was. This underestimation of the temperature is typical and has already been found in comparable settings [40]. In terms of the subjects' climate comfort, the temperature evaluations for the chest and face were the most relevant predictors. This was not surprising, as the density of cold sensors is the highest in the human face and breast region, which leads to an increased sensibility of these body areas. Regarding air draught, however, comfort evaluations of the upper legs were most relevant for the prediction of the climate comfort (Table 5).

The strongest correlation between the objective and subjective data was found for the air draught sensation and the equivalent temperature (and/or LMV) with $r = -0.28$ ($p = 0.09$). This result was to be expected as the equivalent temperature is a function of air temperatures, radiant temperatures and local air velocity, i.e., local air draught has a strong effect on the equivalent temperature (and the local mean vote). The medium correlation of $r = 0.26$ between climate comfort and equivalent temperature was also expected and in good agreement with former findings [41]. The other two relevant subjective variables – temperature sensation and temperature estimation – were in the same range as the equivalent temperature. Surprisingly, there was no correlation between temperature sensation or estimation and equivalent temperature. A possible explanation could be that the variances of the sensation and the estimation variables were too small since the underlying objective temperature was constantly at 27 °C. The sensation and estimation of the temperature could only be influenced by the air speed of the nozzles. This restriction of variance made a correlation unlikely. It is possible that an experimental setting that includes a variation of the room temperature would result in a higher correlation between temperature sensation and equivalent temperature.

6. Conclusions

An experimental study on the application of a PECS based on personalized air nozzles was performed in a generic train compartment. At an increased mean temperature of $T_{im} = 27$ °C in the compartment, it was possible to adjust the perceived temperature using the air nozzles. Thermal comfort was acquired objectively and subjectively based on measurements of the local equivalent temperatures and on subject trails with 40 volunteers. In three different phases, the subjects could individually adjust the air nozzles (t_i), had no air nozzles at all (t_0) and finally were exposed to an automatic setting of the nozzles (t_a). The latter reproduced the individual settings of the t_i phase but the subjects could not readjust the nozzles during this phase. Subjective comfort was assessed using questionnaires in each phase. The objective comfort was assessed in pre-tests for the different nozzle settings and in post-test for all 40 individually chosen configurations.

Five main research questions were addressed by our study:

- Which local airflow rates of PECS's the different air nozzles are chosen by the subjects? Are there preferred settings or settings which are not used?
  - All subjects chose different settings. However, the results (c.f. Table 3) also showed that the head nozzle was, on average, on the lowest value (42% of maximum volume flow rate) and was mostly set to "low" or "medium", while the upper chest and the arms nozzles reached the highest value on average (64.4% and 64%) and were mostly set to "high" or "medium". The leg nozzles were also operated mostly on "medium" or "high", however, a little lower on average (61%) compared to the chest and arms nozzles.
- Which range of equivalent temperatures needs to be available to address the demands of the test persons?
  - We can conclude from the boxplots of the equivalent temperatures of the 40 subjects' settings (c.f. Fig. 7) that a) different temperatures are chosen for different body parts, b) the variation of the values depends on the body part and c) the 40 subjects have strongly individual demands reflected by variations as large as 11 K (whisker to whisker) or 6.5 K (IQR).
- What is the subjective thermal comfort evaluation of the installed PECS for an increased mean temperature in the compartment?
  - The evaluations for temperature, air draught and climate comfort were higher for the two phases with a nozzle (t_i and t_a) than for the phase without nozzle (t_0, Table 4). The air draught was perceived to be stronger in t_i and t_a than in t_0. This means that the subjects successfully used the nozzles to improve their climate comfort compared to the condition without nozzle.
- What effect does the individual vs. automatic control of the PECS have?
  - It made hardly any difference whether the nozzles were set by the passengers themselves or whether their saved settings were used for an automatic setting which is in line with former findings [8,38, 39].

- Which correlations can be found between chosen settings, individual comfort evaluation and objective measures such as local mean vote?
  - The strongest correlation between objective and subjective data was found for the air draught sensation and the equivalent temperature (and/or LMV) with $r = -0.28$ ($p = 0.09$).
  - Surprisingly, there was no correlation between temperature sensation or estimation and equivalent temperature. A possible explanation could be that the variance of the sensation and the estimation variable was too small since the underlying objective temperature was constantly at 27 °C. The sensation and estimation of the temperature could only be influenced by the air speed of the nozzles. This restriction of variance made a correlation unlikely.

In conclusion, the individual nozzles helped to address the subjective demands on thermal comfort and that they could compensate for increased mean temperatures in the compartment. In upcoming studies, different arrangements of the individual air nozzles will be analyzed in the generic train mock-up and in a stationary ICE train laboratory. Further, additional measurements of the 3D flow fields of the multi-jet air nozzle will be performed to investigate the local differences, e.g., between right and left body part, in more detail.

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CRediT authorship contribution statement

Daniel Schmeling: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Oliver Zierke:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julia Maier:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tobias Dehne:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **André Volkmann:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Claudia Marggraf-Micheel:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Panja Goerke:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table 7
English version of all questionnaires used.

Item	Content	Rating scale
Climate parameter sensation & evaluation		
1a	I perceive the air draught on my face as …	1 = not at all, 4 = neutral, 7 = very strong
1b	… and this is what I evaluate as ...	1 = very uncomfortable, 3 = neutral, 5 = very comfortable
2a	I perceive the air draught on my chest as …	1 = not at all, 4 = neutral, 7 = very strong
2b	… and this is what I evaluate as ...	1 = very uncomfortable, 3 = neutral, 5 = very comfortable
3a	I perceive the air draught on my hands as …	1 = not at all, 4 = neutral, 7 = very strong
3b	… and this is what I evaluate as ...	1 = very uncomfortable, 3 = neutral, 5 = very comfortable
4a	I perceive the air draught on upper legs as …	1 = not at all, 4 = neutral, 7 = very strong
4b	… and this is what I evaluate as ...	1 = very uncomfortable, 3 = neutral, 5 = very comfortable
5a	I perceive the air draught on my feet as …	1 = not at all, 4 = neutral, 7 = very strong
5b	… and this is what I evaluate as ...	1 = very uncomfortable, 3 = neutral, 5 = very comfortable
6a	I perceive the temperature on my face as …	1 = very cold, 4 = neutral, 7 = hot
6b	and …	1 = very uncomfortable, 3 = neutral, 5 = very comfortable
7a	I perceive the temperature on my chest as …	1 = very cold, 4 = neutral, 7 = hot
7b	and …	1 = very uncomfortable, 3 = neutral, 5 = very comfortable
8a	I perceive the temperature on my hands as …	1 = very cold, 4 = neutral, 7 = hot
8b	and …	1 = very uncomfortable, 3 = neutral, 5 = very comfortable
9a	I perceive the temperature on upper legs as …	1 = very cold, 4 = neutral, 7 = hot
9b	and …	1 = very uncomfortable, 3 = neutral, 5 = very comfortable
10a	I perceive the temperature on my feet as …	1 = very cold, 4 = neutral, 7 = hot
10b	and …	1 = very uncomfortable, 3 = neutral, 5 = very comfortable
11a	I perceive the air draught in the railway car as …	1 = not at all, 4 = neutral, 7 = very strong
11b	… and this is what I evaluate as ...	1 = very uncomfortable, 3 = neutral, 5 = very comfortable
12	Please estimate the temperature in the railway car (°C).	open
13a	I perceive the temperature in the railway car as …	1 = very cold, 4 = neutral, 7 = hot
13b	and …	1 = very uncomfortable, 3 = neutral, 5 = very comfortable
14	With the climate in this railway car, I am …	1 = very dissatisfied, 5 = very satisfied
Physiological well-being		
15a	I feel cozy.	1 = not at all, 3 = more or less, 5 = completely

(*continued on next page*)

Table 7 (*continued*)

Item	Content	Rating scale
15b	I agree with the current state of my body.	
15c	I have a pleasant feeling on my skin.	
15d	I can enjoy the current state of my body.	
15e	I feel comfortably warm.	
15f	My body feels comfortable.	
15g	I am familiar with the current state of my body.	

Data availability

Data will be made available on request.

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