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DOMUS

Design Optimisation for efficient electric vehicles based on a User-centric approach

DOMUS – Deliverable Report

D1.3 Holistic Passenger Comfort Model for Vehicles

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1 Publishable summary

1.1 Background

The aim of this deliverable is to provide a basis for assessing passenger comfort in a holistic model that quantifies comfort and includes based thermal comfort complemented by other factors.
The factors considered have been identified in the list of priority factors influencing comfort identify by literature review and expert inputs in D1.1.

The comfort model developed in this task returns a comfort indicator value. This comfort indicator is used by the assessment framework developed in D1.2. which provides a user-centric assessment of the energy use of a car cabin and climate control system while ensuring it meets expectations for comfort and safety.
The mathematical holistic comfort model can also be interpreted from a psychological perspective and thus provide a more intuitive explanation and reasoning about why the various factors (such as, scent or light) have a particular effect on comfort perception.

The comfort model helps define the set of sensors and additional active comfort components and is used in for the definition of user-centred control strategies. The comfort model as part of the assessment framework will then also be used for virtual assessments of technical/technological solutions developed within DOMUS.

1.2 Task objectives

The objectives of the sub-task carried out are the following.

Context understanding:
- develop a contextual understanding of holistic comfort from a psychological perspective.

Methods:
- develop overall methods allowing comparability and generalisability and replicability of the data collection over the five study locations
- develop individual study methods allowing to assess influences on holistic comfort of factors identified

Analysis – mathematical modelling:
- only include comfort aspects shown to be significant
- predict subjective comfort significantly more accurately compared with the base comfort model

1.3 Methods

All involved partners to the task of defining overall methods through regular teleconference and face to face workshops (activity started as part of T1.1 and preliminary results have been reported in D1.1 and D1.2).

The methods consist of:

- Alignment of **contextual understanding** of holistic comfort
- A defined set of **comfort factors** that will be manipulated in at least one of the five study
- **Environmental factors** and **individual factors** that have to be treated as independent variables in the studies (including a description of target levels and measurement set-up when relevant)
- A list of **dependent variables** to be collected
- General guidelines regarding the **procedure** to follow in the studies, including questionnaire templates allowing to collect data regarding dependent variables and certain individual factors
- **Analysis** of the acquired datasets

Table 1: Factors and dependent variables considered in the overall methods

Comfort factors	Environmental factors	Individual factors	Dependent variables
- radiation wavelength and irradiance - asymmetrical (sun) radiation - air flow - sound - task - ambient scent - ambient light colour	- air temperature - radiation - relative humidity - air velocity - air quality - experimental space and seating type - lighting experimental space - ambient scent	- demographic - clothing - thermal and activity history - metabolic rate - thermal sensibility - acoustic sensibility	- thermal sensation - comfort appreciations - task load

This deliverables also presents detailed individual study methods including description of the study designs, tasks, apparatus, stimuli, set-up and procedure.

1.4 Results

The key results include:

1. The DOMUS consortium collected and summarised experimental datasets from each of the 5 involved partners, involving a total of 149 participants over an elapsed duration of 242 hours (see details in Table 2).

Table 2: Overview of experimental work in terms of participants and duration

	Participants	Duration per participant	Total duration	
	(#)	*(minutes)*	*(minutes)*	*(hours)*
COV	10	30	300	5.0
CRF	31	40	1240	20.7
IKA	29	240	6960	116.0
TME	47	60	2820	47.0
VIF	32	100	3200	53.3
DOMUS studies	**149**	**470**	**14520**	**242.0**

2. We produced comparative results for a series of models and a variety of sub-selections of the experimental datasets. The full aggregated dataset produces a binary comfort classifier with Logistic Regression that is accurate 78% of the time.
3. In comparison, the baseline thermal comfort model was only able to correctly predict comfort 58% of the time for the same dataset.
4. This deliverable provides the model parameters and associated equations for the best performing model.

These results meet the requirements set out in the objectives for this part of the project and provide a strong foundation for the remainder of the DOMUS work to build upon.

2 Contents

3 Tables and abbreviations

3.1 Table of figures

3.2 Table of tables

3.3 Table of pictures

3.4 Abbreviations

Symbol / Shortname	
°C	Degree Celsius
µm	Micrometre
A/C	Air conditioning
BCM	Berkeley Comfort Model
clo	Clothing insulation
dB	Decibel
dB(A)	A-weighted Decibel
DNN	Deep neural network
ECU	Electronic Control Unit
EV	Electric Vehicle
HCM	Holistic Comfort Model
HVAC	Heating, ventilation, and Air Conditioning
IR-A	Infrared radiation - type A (near)
IR-C	Infrared radiation - type C (far)
K	Kelvin
kph	Kilometres Per Hour
kW	Kilowatt
m	Meter
MET	Metabolic Equivalent of Task
min	Minutes
ml	Millilitre
mm	Millimetre
NVH	Noise, Vibration and Harshness
OEM	Original Equipment Manufacturer

Symbol / Shortname	
PMV	Predicted Mean Vote
ppm	Parts per Million
rpm	Revolutions per Minute
s	Second
SEM	Standard Error of the Mean
SET	Standard Effective Temperature
SPL	Sound Pressure Level
W	Watt

4 Introduction

4.1 Objectives

The aim of this deliverable is to provide a basis for assessing passenger comfort in a holistic model that quantifies comfort and includes basic thermal comfort complemented by other factors, such as acoustics, thermal asymmetry, radiation specifications, user task, or interior lighting and scent.
The effect of priority factors, identified in D1.1, on holistic comfort will tested in different studies organised in five locations following common overall methods. Their relevance to be included in the model will then be assessed in a conjoined analysis of the data collected.

The outputs of the deliverable includes:
- A detailed description of the methods allowing to replicate the studies conducted
- A holistic comfort model that returns a value which is the comfort indicator (binary value, according to the fitness function definition in D1.2).
- The model will be delivered in the form of a validated/tested program code with a commented list of input parameters (aligned with the interface definitions of beneficiaries)
- A description of holistic comfort perception allowing a qualitative interpretation of the model from a psychological perspective. This would allow one to refer to some major principles behind the model additionally to the mathematical model itself.

The following points should allow one to confirm whether or not the objectives are reached:
- Only comfort aspects shown to be significant are included in the model
- The holistic model predicts subjective comfort significantly more accurately compared with the base comfort model
- The holistic comfort models should correctly predict the perception of comfort for a number of use cases and scenarios with an accuracy of 10% against measured parameters.

4.2 Relationship to DOMUS objectives

DOMUS project aims to reduce energy consumption of electric vehicles (e.g. minimize consumption of components, reduce losses, remove unnecessary consumptions). The car cabin's heating and cooling system is the car's largest auxiliary load, however this system is closely related to personal comfort (critical to customer satisfaction) and some of this functionality is needed for safety (e.g., defogging the windscreen).

The overall aim of WP1 is to provide an efficient virtual method for the user-centric assessment of the energy use of a car cabin and climate control system while ensuring it meets expectations for comfort and safety (assessment framework described in D1.2).
To achieve this, it is necessary to first observe, analyse, and model the user's perception and requirements for comfort, identifying the priority and contribution of comfort factors by studying the users' comfort response to their environment. This statement summarizes the method employed in the present deliverable (D1.3) leading to the holistic comfort model presented as result. The jury experimentations that this deliverable presents, account for the priority factors for estimating comfort identified in D1.1. In the studies conducted, these priority factors are either manipulated (with the objective to observe their influence on holistic comfort) or treated for as independent variables (with the objective to ensure comparability and generalizability of the results).

This deliverable also works towards Objective #1 of the DOMUS project, which states that the work will "acquire a thorough understanding of all factors influencing comfort perception and capture the capability to improve EV energy efficiency while maintaining optimal user experience".

4.3 Relationship to other work packages and tasks

This deliverable is part of WP1. The aim of this work package is to provide an efficient virtual method for the user-centric assessment of the energy use of a car cabin and climate control system while ensuring it meets expectations for comfort and safety. The assessment framework itself has been described in D1.2

(T1.1). This deliverable, the main output of T1.2, aims at providing an improved comfort prediction compared to a base thermal comfort model by taking into new factors related to a more holistic understanding of comfort perception. Remaining WP1 activities (T1.3 and T1.4) will deliver cabin models (respectively 3D and 1D) for simulating thermal and acoustic behaviour of the Fiat 500e cabin (vehicle used for assessment).

As shown on Figure 1, results from WP1 will be used in WP2 focusing on advanced cabin design and virtual assessment as well as in work packages focused on developing technical/technological solutions (WP3, 4, 5). The present deliverable and the comfort model it includes will be specifically used in WP2 as part of the virtual assessment. The comfort model as well as its qualitative interpretation will also be provided as input to WP5 for the definition of sensors sets and additional active comfort components as well as for the definition of user-centred control strategies.

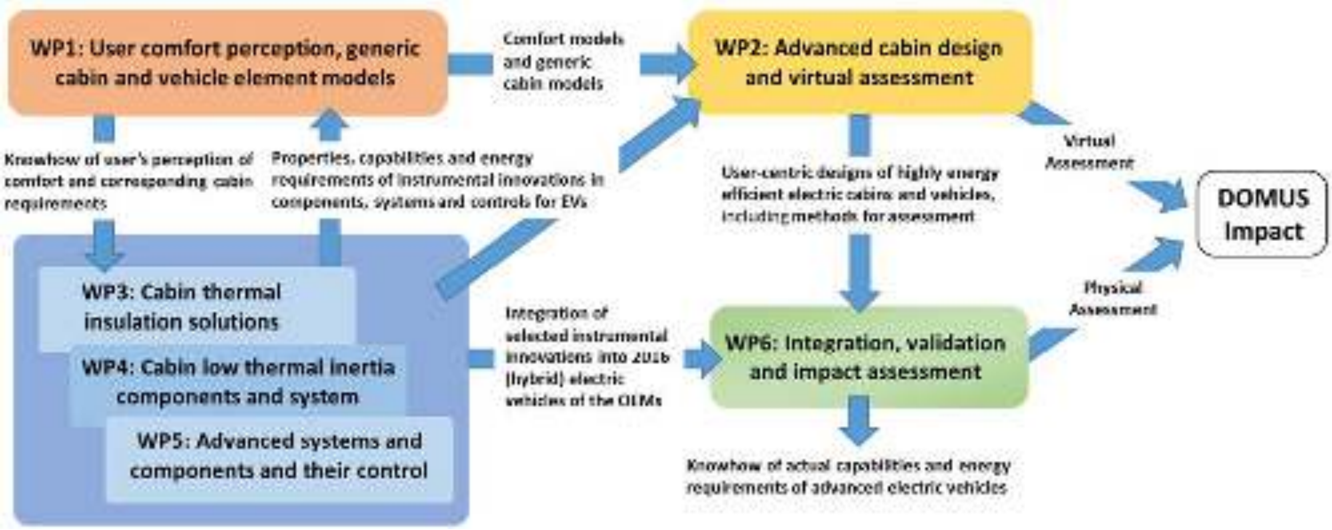


Figure 1: Interaction between work packages within DOMUS

4.4 Priority factors identified

In D1.1, a set of priority factors for estimating comfort was identified based partly on existing literature and partly on consortium expertise. The following factors were identified:

- Operative temperature or equivalent temperature
- Primary factors influencing acoustic comfort
- Cognitive factors of comfort
- Light as comfort moderating factors
- Gender
- Recent temperature history
- Ambient scent
- Psychophysiological measurements
- Thermal asymmetry of the body
- Humidity
- Air quality

These factors are all taken into account in the overall methods and are represented in the dataset collected in each study. For each variable considered, section 5 gives further details about common measurement set-ups and/or control guidelines.

4.5 Holistic comfort from a psychological perspective

Comfort expectations for automotive vehicle cabins go beyond mere physiological comfort as indicated by the inclusion of many non-driving related features such as entertainment and information systems and aesthetic styling characteristics. Especially as driving gets automated these trends are expected to continue as vehicles become increasingly places to work, communicate, and relax. Even in today's modern vehicles, designers speak about empathetic assistants who sense human emotions and appropriately adjust to provide optimal occupant experiences. This leads toward a wider understanding of comfort that goes beyond physiological comfort: sitting in a comfortable chair at perfect room temperature for extended time may not result in the experience of overall comfort if the experiencers' activities are not taken into account. Therefore, it seems that in order to understand the comfort experiences of modern drivers and passengers comfort models would need to incorporate the human experience to a greater extent. Whereas physiological comfort is mainly influenced by the interaction of the body with the environment, a positive experience of holistic comfort, we think, needs to take into account the experience of satisfaction in the vehicle environment. Human satisfaction experiences have been investigated in many areas, but especially in product design (e.g. [Seva et al., 2011] [Gaspar et al., 2014]) and workplaces where factors of satisfaction include autonomy, control, tasks and task identification (e.g. Humphrey et al., 2007).

According to the comfort theories Vink and Hallbeck (2012), comfort is influenced by the interaction between the human, the activity, the product, and the environment, which results in body sensations that are modified by comfort expectations, resulting in feelings of comfort, discomfort, or no feelings.
Naddeo et al. (2015) expanded this model toward mattress comfort and measured the impact of expectation on comfort judgements. We are expanding this model further by including psychological moderator processes for two different types of comfort aspects: physiological comfort perception and the experience of satisfaction (see figure below). Each of the main components is briefly discussed next.

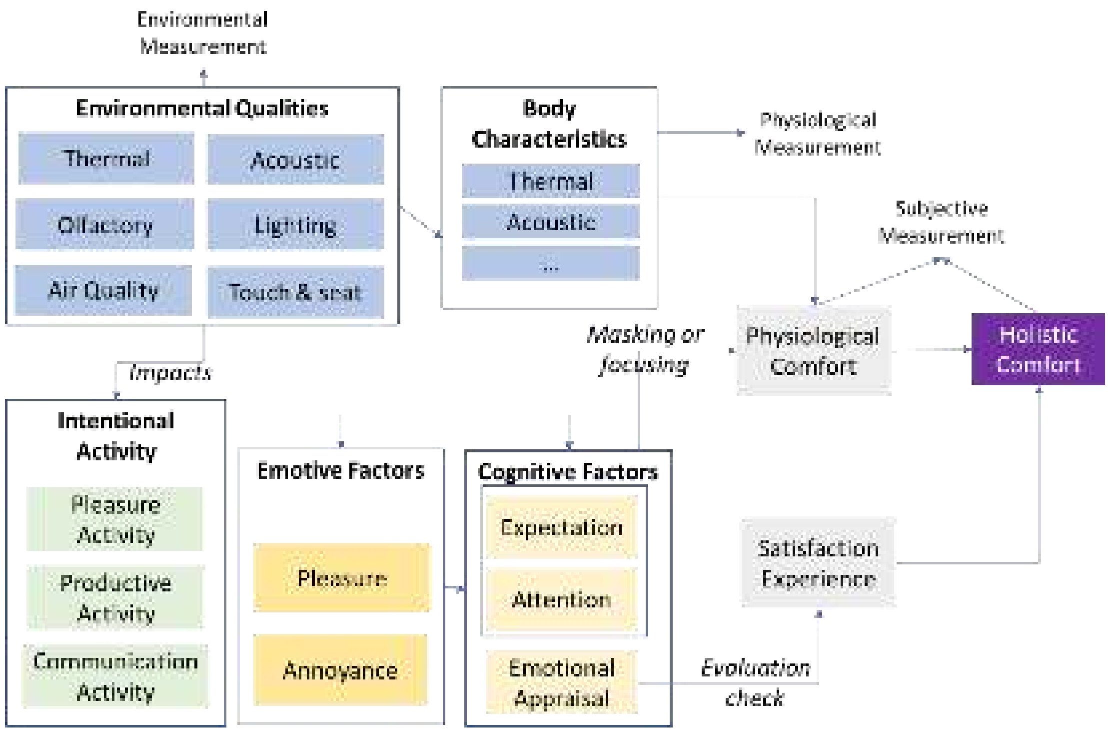


Figure 2: Holistic comfort from a psychological perspective

Environmental qualities describe the aspects of the environment with which the human body interacts as basis of a physiological comfort assessment. In the Vink-Hallbeck model (Vink & Hallbeck, 2012) these qualities are ordered around person, product characteristics, and usage/task as well as the working environment, but in the end what is sensed by the human body are thermal, acoustic, olfactory, lighting, haptic and seating, and air-quality characteristics.

The specific body characteristics interact with the environmental characteristics so that physiological sensations are formed as indicated in Vink-Hallbeck's model. Clothing for example influences thermal sensations and the shape of the body impacts the seating comfort experience. Both, body characteristics as well as the interaction between environmental qualities and body characteristics can be measured using physiological measurements.

The experience of physiological comfort is moderated by cognitive factors effectively masking or emphasizing the physiological perceptions. This moderation effect of cognitive processes on perception is for example in the focus of the investigation of chronic pain (Ciccerone & Grzesiak, 1984). Also, Luo et al. (2014) investigated the comfort of passengers while sitting for a prolonged period of time (e.g. in-flight entertainment) and environmental conditions have been shown to impact passenger comfort. This may be explainable by the fact that attentional resources are pulled from the physiological experience toward other areas or activities. This may allow one to endure physiological discomfort over prolonged amounts of time. Comfort expectations may further attenuate the physiological comfort thresholds: people report experiencing the comfort of a mattress to be higher when it is introduced as a high-quality product versus a low-quality product (Naddeo et al., 2015).

Intentional activities represent the activities that the vehicle occupant is engaged in and form the basis for the cognitive appraisal processes of satisfaction or dissatisfaction. Aspects of satisfaction in the work context are listed for example by Humphrey et al. (2007) and include autonomy (see e.g. [Luo et al., 2014]), level of control, skill variety, task significance, and identity as well as feedback. User satisfaction models have been postulated in the design community (e.g. [Seva et al., 2011] [Gaspar et al., 2014]). Altogether these factors are likely different from physiological comfort which does not require emotional appraisals. Whereas the perception and evaluation of physiological comfort is based on expectations and the availability of attention to filter, suppress, or emphasize the physiological perceptions, emotional appraisal processes should be involved in the decision concerning the experience of satisfaction or dissatisfaction (see e.g. [Smith & Ellsworth, 1985]). The activity itself becomes part of the comfort experience. The environment may more or less support the conduct of these activities. Furthermore, emotive product characteristics such as aesthetic and usability may further strengthen the experience of satisfaction.

4.6 Baseline thermal comfort model

D1.2 provides a detailed review of thermal comfort models including the Predicted Mean Vote (PMV) developed by Fanger (1970), the Berkeley Comfort Model (BCM) that originates from the PhD thesis of Zhang (2010), Standard Effective Temperature (SET and SET*) from the work of Gagge (1986), Nilsson et al., (1999) and Madsen et al.'s (1984) Equivalent Temperature, and the more recent Adaptive Thermal Comfort models proposed by Humphries, Nicol, de Dear, and many others.

The idea of a `baseline' thermal comfort model is due to the limited thermal experiments able to be conducted within the DOMUS project. If only a restricted set of subjective trials are available, then a model formed on the basis of those limited trials might not generalise well. In particular, it might not be able to extrapolate well to cases that have not been seen in the trials. To counter this, we propose to devise the model as an addendum to an existing or baseline model.

The choice of a baseline thermal model is based on:

1. the choice of sensors used for the experimental trials
2. the ability of the baseline model to match reasonably well with experimental trials.

The choice of sensors is described elsewhere in this document and is largely similar to the experimental work in the OPTEMUS project, with additions for measurement of air quality, humidity, and so forth. This choice removes the Berkeley Comfort Model from the available set since skin temperature was not measured.

Ockham's razor suggests that the best baseline model to use is the simplest one that explains the data. Another way to phrase this is to aim for a simple model that provides the most accurate prediction of subjective comfort based on unseen data (data that was not used to produce the model). This approach has led to the recent successes of the Adaptive Comfort Model for the built environment. For this reason, PMV is not preferred since it is a complex model that is now known to not produce accurate predictions of subjective comfort even for its target environment (buildings). Thus to make the final choice of baseline model, it is necessary to evaluate both the complexity of the model and its ability to accurately predict subjective comfort for the DOMUS experimental results.

4.7 Approach towards a holistic model

This section discusses that part of the *methodology* that explains why the experiment is rigorous from a theoretical point of view without discussing the details of the method (see section 5 for this). It then goes on to discuss the methodological approach to deriving a model from the experimental data.

The DOMUS approach towards a holistic comfort model is methodologically based on work from the Adaptive Comfort literature. This theoretical line of work arose from the realisation that existing thermal models (such as, PMV) didn't agree with field experiments. A specific example of this is that comfort temperatures in hot climates are much higher than comfort temperatures in more temperate climates. This realisation, for example, led to the idea that in a hot climate, it would be more economical to naturally ventilate a building rather than strictly control the air temperature.

The field experiments for Adaptive Comfort were derived from interviewing subjects in a natural environment, without necessarily controlling the temperature. Similarly, in DOMUS, we have interviewed subjects about their thermal comfort in a combination of laboratory and naturalistic settings. Although it might have been preferable to have completely natural environments, such as interviewing subjects and measuring the environment during normal car use, this was not possible within the scope of the project.

In the Adaptive Comfort literature, experimental data sets were pooled from separate studies. These studies were separate in the sense that they were performed by different researchers in different geographical regions. Similarly, within DOMUS, five separate groups have performed experiments within laboratory and naturalistic environments. Laboratory conditions were typically used to allow inclusion of radiant panels, particular lighting or aromatic scents. The naturalistic environment trials were performed in a stationary vehicle.

There are a number of *threats to validity* for this work that are worthy of attention:

1. The environment may not be sufficiently natural. Human subjects may perceive thermal or overall comfort differently because they are in a laboratory environment. In principle, this might be overcome by staging experiments to occur during the subject's usual use of the vehicle.
2. Human subjects may try to please the experimenter by giving answers that they think the experimenter wants to hear. For example, they may put up with very uncomfortable conditions and report them as only slight discomfort or may try to be especially sensitive to thermal variation and report discomfort when ordinarily they would consider themselves comfortable.
3. The experiments do not test situations that can occur with normal car use, including:
    a. entering a tunnel where air pollution is high
    b. the "sloshing around" movement of hot and cold air within the cabin during acceleration or cornering
    c. the opening of windows to ventilate the car cabin or expel cigarette smoke
4. Only a limited cross-section of the human populace (or car occupants) is used and this sample may be biased (e.g., to subjects with a strong educational background)

These threats to validity, while significant, are not uncommon in this type of work. Nevertheless, they may lead to imperfections in the resulting model.

4.7.1 Deriving a model

Adaptive Comfort departs from previous approaches to modelling thermal comfort by attempting to find simple, linear models that explain the data. This is in contrast to previous approaches, such as PMV, that involve formulas that are difficult to calculate and sometimes require complex iterative algorithms to produce each thermal comfort estimate. Similarly, in DOMUS, we attempt to find the simplest possible model that explains the data.

The influence of certain factors such as radiant temperature, humidity and airflow speed on thermal comfort perception are known and are represented in many existing thermal comfort models such as Fanger's Predicted Mean Vote (PMV), the Berkeley comfort model and the Equivalent Temperature model. However, some research suggest that comfort may entail more than thermal comfort sensation and may include such comfort dimensions as acoustic and olfactory comfort, and to this end, we define "holistic comfort". For this reason, other non-thermal factors, such as light colour, scent type and sound level have to be included in existing comfort models in order to accurately reflect holistic comfort perception. An extended list of all factors with the potential of influencing holistic comfort is given below:

- i. Air temperature (head, trunk, feet)
- ii. Airflow speed (head, trunk, feet)
- iii. Radiant temperature (head, trunk feet)
- iv. Relative humidity
- v. CO_2 concentration
- vi. Lux level
- vii. Light colour
- viii. Scent
- ix. Sound level (dB)
- x. Task (measured by the NASA driving activity load index)
- xi. Outdoor temperature
- xii. Indoor temperature
- xiii. Clothing level
- xiv. Age
- xv. Gender
- xvi. Weight
- xvii. Height
- xviii. Temperature/ activity history
- xix. Temperature sensitivity
- xx. Noise sensitivity

The holistic comfort model is therefore a mathematical model, obtained by machine learning, that extends the existing thermal comfort model to include other comfort dimensions such as lighting, acoustics, and olfactory sensations. In its simplest, the model seeks to establish the relationship between different comfort factors and the holistic comfort perception. If we consider the set of all comfort factors as the vector $\boldsymbol{F}$, and $\boldsymbol{C_{hol}}$ as the categorical output representing a cabin occupant's perception of their comfort that takes values from the example set: {"Terrible", "Very bad", "Bad", "Slightly bad", "Neither good nor bad", "Moderately good", "Good", "Very good", "Excellent"}, then the holistic comfort model gives a function f such that:

$$\boldsymbol{C_{hol}} = f(\boldsymbol{F}, \boldsymbol{c_t})$$

where $\boldsymbol{F}$ is the vector denoting the set of all comfort factors,
$\boldsymbol{C_{hol}}$ is the cabin occupant's comfort perception or response, and
$\boldsymbol{c_t}$ is an existing thermal comfort model

Since this function f is unknown, the approach taken is an extensive experimentation that involves the variation and/or measurements of the different comfort factors and the existing thermal comfort model in order to determine the comfort responses; the data obtained from these experimentations then yield themselves to being trained via machine learning techniques in order to approximate the function f.

To this end, the following elements are critical to the development of the holistic comfort model:

1. An existing thermal comfort model
2. Measured comfort factors
3. Holistic comfort perceptions – subjective rating of occupant's comfort sensations.

It is worth noting that the comfort factors given in $\boldsymbol{F}$ do not all affect the holistic comfort to the same extent, and it is, in fact, possible that some factors will have no effect on the holistic comfort whatsoever. It is the task of the holistic comfort modelling to reveal the influence of the different factors on the holistic comfort perception. Thus, all comfort factors are assumed to have an effect on the holistic comfort *a priori* and are therefore required to be included in the training of the holistic comfort model.

5 Overall methods

5.1 Introduction

As stated in the Grant Agreement (GA #769902), the objective of the studies is to research new factors influencing comfort not yet taken into account in existing comfort models. Jury experimentations aiming at evaluating the impact of these new factors have been organised in 5 locations. The factors that are manipulated are described as comfort factors (section 5.2).

Overall methods have been created in order to ensure that the data collected is compatible and allows the creation of a new model. For this purpose, a workshop was organized in Munich in July 2018 and regular teleconferences were scheduled (planned every two weeks) during the period May-November 2018 with the partners involved.

As a result, a list of factors to be considered as independent variables was defined together with their level (i.e. value to target when factor is not manipulated) as well as a control or measurement set-up ("environmental factors" in section 5.3 and "individual factors" in section 5.4). Partners also aligned on a common dependent variables (i.e. sensation, comfort and task load values) taking the form of questionnaires (section 5.5) and on a common procedure (section 5.6). The measures taken, listed above, allow to guarantee comparability and generalizability of the data collected at the different study locations.
The factors considered in the holistic comfort experimentations originate in the priority factors for estimating comfort identified and listed in D1.1.

The table below describes factors and dependent variables considered by each partner. Factors listed as "comfort factors" are the ones considered as experimental factors in partners' experimentations. Their manipulation will allow to gain knowledge about comfort in automotive cabins.

Table 3: Factors and dependant measures considered by each partner

Partner	*Comfort factor*	*Environmental factor*	*Individual factor*	*Dependent variables*
COV	"Natural" environment - Air temperature - Radiant temperature - Air flow speed - Sound - Ambient scent	- Humidity - Air quality - Task - Space & seating	- Demographic - Clothing - Thermal sensitivity - Acoustic sensitivity - Metabolic rate	- Thermal sensation - Thermal comfort - Acoustic comfort - Visual comfort - Seating comfort - Olfactory comfort - Overall comfort - Task load
CRF	- Sun radiation - Air flow (velocity and outlet position)	- Air temperature - Radiation - Humidity - Sound - Air quality - Task - Space & seating - Space lighting	- Demographic - Clothing - Thermal sensitivity - Acoustic sensitivity - Metabolic rate	- Thermal sensation - Thermal comfort - Acoustic comfort - Visual comfort - Seating comfort - Olfactory comfort - Overall comfort - Task load
IKA	- Radiation wavelength and irradiance (for different air temperature)	- Air temperature - Sound type - Seating - Space & seating - Task	- Demographic - Clothing - Thermal sensitivity - Acoustic sensitivity - Metabolic rate	- Thermal sensation - Thermal comfort - Acoustic comfort - Seating comfort - Olfactory comfort - Overall comfort - Task load
TME	- Ambient scent (for different air temp.)	- Air temperature - Radiation	- Demographic - Clothing	- Thermal sensation - Thermal comfort

	- Ambient light colour (for different air temp.)	- Humidity - Sound type - Air quality - Task - Space & seating - Space lighting	- Thermal sensitivity - Acoustic sensitivity - Metabolic rate	- Acoustic comfort - Visual comfort - Seating comfort - Olfactory comfort - Overall comfort - Task load
VIF	- Sound - Task	- Air temperature - Air quality - Space & seating	- Demographic - Acoustic sensitivity - Metabolic rate	- Thermal comfort - Acoustic comfort - Visual comfort - Seating comfort - Olfactory comfort - Overall comfort - Task load

5.2 Influences on holistic comfort

The following factors have been manipulated by partners during their experimentations. Their manipulation will allow us to gain knowledge about comfort in automotive cabins. They all belong to the priority factor list established in D1.1. In this section, each comfort factor will be introduced. Levels and details about the set-up used in experimentations will be described for each partner experiment in section 6.

As indicated in Section 4.7.1, not all the comfort factors identified in the priority factor list will influence holistic comfort to the same degree. The holistic comfort model provides a framework to evaluate the influence of each comfort factor on the overall passenger holistic comfort, by finding the partial derivative of the comfort score with respect to a given comfort factor. The holistic comfort model is of the form:

$$\boldsymbol{C_{hol}} = f(\boldsymbol{F}, \boldsymbol{c_t})$$

where $\boldsymbol{F}$ is the vector denoting the set of all comfort factors,
$\boldsymbol{C_{hol}}$ is the cabin occupant's comfort perception or response that takes values from the example set: {"Terrible", "Very bad", "Bad", "Slightly bad", "Neither good nor bad", "Moderately good", "Good", "Very good", "Excellent"}, and
$\boldsymbol{c_t}$ is an existing thermal comfort model

The exact form of the function f will be determined in Section 7, based on the best performing machine learning model that best explains the experimental data.

5.2.1 Radiation wavelength and irradiance (for different air temperature)

Holistic comfort perception is moderated by various factors like olfactory, acoustic, visual as well as thermal comfort. Models like the PMV (Fanger, 1970) suggest that the thermal balance of a human being is connected to thermal sensation and thus to thermal comfort. This thermal balance of human beings is significantly affected by radiation. For instance, as Cooney (1976) showed for a nude person resting in still air at 20 °C, 60 % of heat is lost by radiation, 25 % by evaporation, 12 % by convection, and 3 % by conduction. Furthermore, the reflectance rate of the human skin depends on the wavelength of the irradiance (Piazena & Kelleher, 2010). As Piazena and Kelleher (2010) substantiates for lightly pigmented skin (see Figure 3), the diffuse reflectance of incident long-wavelength radiation (IR-C radiation, λ ≥ 3 µm) is less than 10 %. For shorter wavelengths (visible light λ = 0.38 µm to 0.78 µm as well as IR-A radiation λ = 0.78 µm to 1.4 µm) the diffuse reflectance shows a maxima of up to about 60 to 70 %. One might conclude that a majority of incident visible light and IR-A radiation which e.g. sunlight is mainly composed of, is therefore reflected by human skin and might not contribute to the thermal sensation of the human body ([Piazena & Kelleher, 2010], [Clark et al., 1954], [Jacquez et al., 1955]).

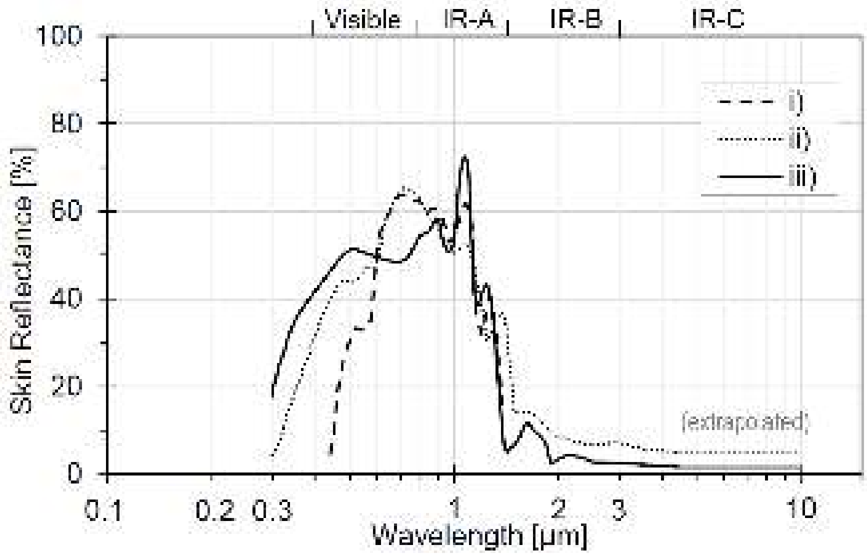


Figure 3: Spectral diffuse reflectance of human skin, based on Piazena and Kelleher (2010). Curves are extrapolated for wavelengths above 4.5 µm. Curve i) represents data from in vivo measurements for lightly pigmented human skin (Piazena & Kelleher, 2010), curve ii) older measurements ([Clark et al., 1954], [Jacquez et al., 1955]) while curve iii) is derived from calculations.

A second skin characteristic is the wavelength-dependent penetration depth of radiation (see Figure 4). IR-A radiation's penetration depth exceeds the skin depth. In contrast, IR-C penetration is mainly limited to the outermost epidermis skin layer (Piazena & Kelleher, 2010). As Streblow (2011) describes, the thermal sensation from a physiological perspective is based on signals of numerous thermoreceptors in the skin, responding to thermal stimuli. Therefore, the penetration depth of radiation, depending on the wavelength should effect the perception of thermal radiation and ultimately the overall thermal sensation, because some wavelengths pass the thermoreceptors (e.g. the spectrum of IR-A) which are mainly located in the upper part of the epidermis, and some wavelengths do not penetrate that deep (e.g. the spectrum of IR-C).

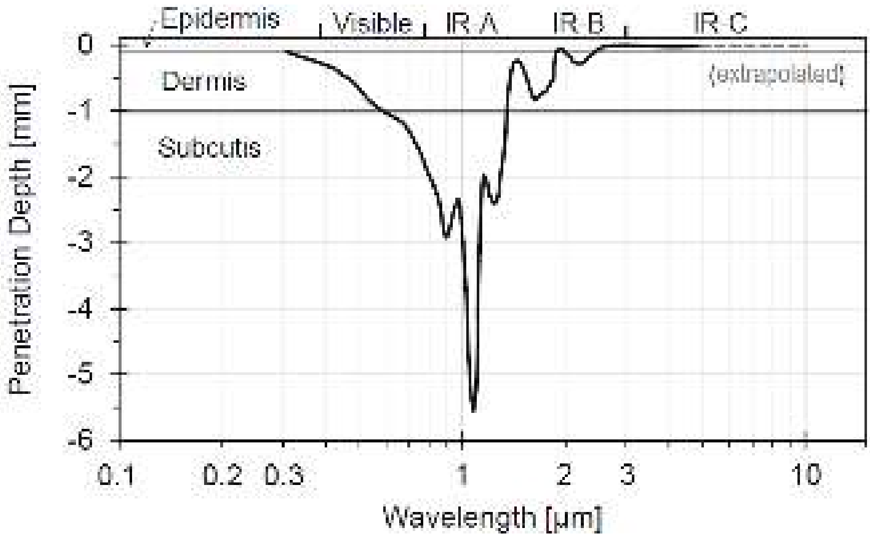


Figure 4: Effective spectral penetration depth into human skin, based on Piazena and Kelleher [10] and extrapolated for wavelengths above 4.5 µm

As outlined above, radiation obviously has divergent physiological effects on the human body, as the effects directly depend on the wavelengths applied. However, current thermal comfort models like PMV (Fanger, 1970) integrate radiative heat exchange with the environment to one single value that is, the mean radiant temperature (ISO 7726). The concept of a mean radiant temperature does not include the actual radiation's wavelength composition. Furthermore, current methods for determining the mean radiant temperature, e.g. with globe thermometers as described in (ISO 7726), disregard physiological characteristics of the skin either. In summary, the simplification done in current models neglects physiological characteristics of human skin and therefore does not appropriately account for thermal radiations present in our environment. That is, current models might over- and/ or underestimate the influence of specific wavelengths of radiation. Based on these considerations and in accordance with the priority factors list in D1.1, ika investigates the influence of radiation wavelength and irradiance level on thermal sensation and holistic comfort.

5.2.2Sun radiation

Although people are in a neutral thermal sensation, they could have a few body parts that are not in thermal comfort condition; this situation always happen when driving a car. To eliminate the local discomfort, it is necessary to work on the source of these causes, whereas the modification of the ambient temperature only is not enough.

The phenomena responsible of the local thermal discomfort are four:

1) local body cooling due to convection air flow

2) body parts cooling or heating due to thermal radiation. This type of discomfort is known as "issue of radiation dissymmetry"

3) cold foot and hot head in the same time, due to high vertical temperature difference

The human body thermal energy is rejected in different ways (thermal convection, conduction and radiation) therefore the ambient temperature only is not enough to define the thermal comfort sensation: other parameters are necessary like the mean radiant temperature, the air velocity and the partial air pressure.

According to the ISO 7726 standard (cfr. § 5.3.1) the mean radiant temperature is calculated from the globe temperature, the air temperature and its velocity. This is an approximate result because:

- the view factors between the globe and the ambient walls are different respect to the human body and the same ambient walls
- the human body has a high cross section that cause a different flow pattern respect to the three sensors globe, thermocouple and anemometer (cfr. § 5.3.1), so the measuring of the last two sensors is approximate

Integrated parameters are introduced to characterize a confined thermal environment reducing the number of parameters and avoiding the calculation of the mean radiant temperature. Among these is the equivalent temperature (Teq) that takes into account the contribution of the parameters that affect the human thermal balance:

$$Teq = f(\text{air temperature, radiant temperature, air velocity})$$

The CRF thermal comfort manikin PACO is equipped with Teq sensors along its body surface and has been used in the experimental campaign managed by CRF.

The aim of this experimental activity, as described below, is to increase the robustness of the holistic comfort model giving the response of the people to the thermal dissymmetries induced by the sun radiation and the air velocity. Together with the standard acquisition system defined by the consortium (cfr. § 5.3.1) the PACO manikin has been used.

The experimental test phases defined by CRF are the following (total time for one test is 40 min):

- Temp. ambient = 22°C
- Humidity = constant 20%
- Test phases (manual controlled HVAC):
    0. dashboard outlets in neutral position, the person gets into the vehicle + subjective rating
    1. reach the comfort at 22°C: A/C on; HVAC mixer handle in middle position (neutral position); blower handle in 1 position; air distribution in dashboard outlets; personal moving of the dashboard vents + subjective rating after 5 minutes
    2. move the dashboard outlets in neutral position, lateral sun simulator switching on + subjective rating after 10 minutes

3. personal moving of the dashboard vents + subjective rating after 5 minutes
4. move the lamp away, dashboard outlets in neutral position + subjective rating after 5 minutes

5/6. close the central right outlet, set the blower at medium and maximum air velocity (3[a] and 4[a] blower handle positions) with the lateral right outlet in neutral position + subjective rating for each air velocity (after 5 minutes for each one)
7. additional phase: open the central outlet and personal moving of it and the lateral one; personal selection of both the air velocity and the temperature (using the mixer and blower handles), then subjective rating after 5 minutes
8. test end

5.2.3 Air flow (velocity and outlet position)

The importance of the air flow effect on the perceived thermal comfort is largely described in the previous paragraph.

Among the parameter involved in the thermo-hygrometric environment (like buildings with air conditioning, vehicles, airplanes, etc.) jet air flows are the most common complaints. The humans can't feel the air speed, but only the local body cooling or heating as a consequence of the air flows. People are sensitive to air velocity on their uncovered parts of the body: the face, the hands and the lower part of the legs.

The amount of thermal energy exchanged with the environment due to the air flows depends on:

- air temperature
- mean air velocity
- air turbulence

The experimental activity performed by CRF with subjective evaluation by the people is described in the following paragraph. The phases 5, 6, 7 describe the setup of the test: in a first time the people are hit by an asymmetrical jet flow at two different velocity without the possibility to modify the air direction. After their subjective rating, in a second time they are allowed to modify the air direction (acting on the dashboard outlet positions) and its velocity (acting on the HVAC blower), with the final subjective rating of the preferred setting.

5.2.4 Ambient scent (for different air temp.)

Ambient scent colour will be research as a possible moderating factor of thermal and overall comfort in an automotive environment. Regarding overall comfort moderation, Bubb (2000) discussed the interactions between comfort from different sensory stimulations and overall (dis)comfort in the automotive context. His analysis led to a pyramid-shape figure inspired by the Maslow pyramid. A discomfort sensation from sensory parameters situated on the lower part of the pyramid are able to convey an overall discomfort regardless of the sensation provided by parameters situated above. According to Bubb, in a bad smelling but thermally comfortable environment, one would feel uncomfortable because of odours: the thermal environment having no influence on the overall comfort perception in this context. The discomfort thresholds for which these kind of interactions apply have nevertheless not been defined.

Figure 5: Discomfort dimensions in automotive environment categorized hierarchically (Bubb, 2000)

The influence of scents on overall comfort can also be positive if the meanings associated to them is positive (Madzharov et al., 2015). Additionally, Brewster et al. (2006) suggested a strong link to memory, attention, reaction times, mood, and emotion. Looking at the holistic comfort model described previously, interaction can therefore be foreseen with other sensory dimensions of comfort. Regarding the moderating effect of ambient scents on thermal comfort the related literature exhibits at this stage and to our best knowledge vague results. As example Jones (2018) used warm scents (e.g. vanilla) and cold scents (e.g. peppermint) to analyse consumers buying behaviour and body temperature perception. Fragrances conveying “cold” and “warm” meanings will also be tested as part of DOMUS experimentations.

5.2.5Ambient light colour (for different air temp.)

Ambient light colour will be research as a possible moderating factor of thermal and overall comfort in an automotive environment. Regarding overall comfort moderation, Bubb (2000) presented “vibration, light” as second most influential aspect of experiencing discomfort in an automotive environment. Additionally, colour have the ability to convey meanings and emotions which make ambient light colour a good candidate to potentially improve overall cabin comfort. Regarding thermal comfort moderation, preliminary findings from the non-automotive context seem promising for applications in this context. For Instance, two studies from Huebner et al. (2016) showed that within buildings shades of blue (6500 K) and yellow (2700 K) ambient light could slightly influence subjectively perceived thermal comfort in a climate chamber. One of the studies focused on comfort rating using thermal comfort surveys and the other used an observational design, where changes in clothing levels were interpreted as thermal discomfort responses. In a two-hour observation by Candas and Dufour (2005) slight differences in comfort perception were observed, when comparing yellow 2700 K and blue 5000 K hues in a slightly warm environment. Another study from Winzen et al. (2013) tested participants in a light laboratory which was modelled after an aircraft cabin. Differences in thermal sensation, but not in comfort perception were found between four different lighting conditions, where two conditions were in yellow hues and two conditions were in blue hues. In summary, the three briefly described studies revealed that these ambient colours contributed to trigger colder or warmer thermal sensation, respectively. Deducted from these findings the present study will examine if similar results can be reproduced in an automotive context (e.g. lighting in peripheral vision only, indirect lighting, and confined space).

5.2.6Sound

The acoustic attributes of vehicle cabins influence the experience of vehicle occupants as they indicate the vehicle’s sportiness, luxury, and general quality of the vehicle (e.g. Genuit 2008). Especially vehicles in higher price segments experience continuous innovation to determine the appropriate methods to dampen the effects of tire, wind, engine, ventilation and traffic noise on the vehicle occupant and achieve a desirable acoustic sound image. Methods to achieve these goals usually involves the use of noise dampening materials but also active sound components that emphasize the experience of an advantageous sound image. The application of such additional methods however usually add weight to the vehicle thereby in general reducing vehicle efficiency. Achieving an appropriate balance among the

trade-offs between vehicle efficiency and acoustic comfort as well as vehicle costs represent an omnipresent optimization task for vehicle designers. Achieving such balance is also a challenge for the design of electric vehicles where motor noise is comparably small compared to internal combustion engines. This also reduces the sound masking effects of internal combustion engines; other noises become audible as the engine sounds are reduced.
Therefore, a task in DOMUS is to investigate the factors that impact acoustic comfort in electric vehicles to ultimately determine ways to reduce the need for inefficient noise and vibration dampening materials while at the same time achieving acceptable comfort. Another DOMUS goal is to quantify the contribution of acoustic comfort to the overall perception of (holistic) comfort where multiple comfort dimensions such as thermal, lighting, and olfactory comfort are joined.

5.2.7 Task

Vehicle occupants engage in driving and non-driving tasks that may impact the perception of comfort. During manual driving, the driver performs the dynamic driving task whereas passengers may engage in other non-driving related activities such as communicating, entertainment, or just watching the outside environment. While traditionally vehicle cabin developments focus around the dynamic driving task, this changes as vehicles are designed for automated driving functionality where drivers engage in new types of activities such as shown in the picture below.

Picture 1: Automated Driving allows for Different Activities that may Impact Comfort Expectations

Therefore, the main question is to what extent do activities that vehicle occupants engage in impact their experience of comfort? Based on a review of existing research, activities may influence the cognitive appraisal processes that result in a comfort judgment. Aspects of satisfaction in the work context are listed for example by Humphrey, Nahrgang, and Morgeson (2007) and include autonomy (see e.g. Luo et al. 2014), level of control, skill variety, task significance, and identity as well as feedback. These task-related factors are different from physiological factors and seem to require an emotional appraisal process rather than perceptions of physiological discomfort. Whereas the perception and evaluation of physiological comfort is based on expectations and the availability of attention to filter, suppress, or emphasize the physiological perceptions, emotional appraisal processes are involved in the decision concerning the experience of satisfaction or dissatisfaction (see e.g. Smith & Ellsworth, 1985). Therefore, the activity itself becomes part of the comfort experience. The environment may more or less support the conduct of these activities. Furthermore, emotive product characteristics such as aesthetic and usability may further strengthen the experience of satisfaction.

5.2.8 Natural environment

Like the experimental method employed by other experimental partners, COV's experimental method looks at investigating the influence of the comfort factors on holistic comfort perception. However, our method is aimed at obtaining experimental data from a real car environment (instead of a cabin simulator) and to mimic realistic user behaviour, in order to validate the holistic comfort model built on the data from the other four experimental partners. Hence, our method differs in a number of ways from the broader DOMUS experimental method as follows:

1) Our experiments are conducted in a real car in a parking lot, rather than in a cabin simulator.
2) The non-traditional comfort factors are not varied intentionally by the experimenter.
3) The environment is not controlled, beyond the control exerted by the car's HVAC, and hence the baseline values are not guaranteed to be met.
4) Participants are not tested for any test cases. Instead, the ambient environment is allowed to change naturally, while the cabin occupant is encouraged to make changes to the HVAC settings to feel comfortable. Measurements of the comfort factors are carried out right when the participant enters the car, and it is repeated every 3 minutes – after which the participant indicates their holistic comfort perception – for up to 30 minutes.
5) In order to further introduce environmental variation *per subject*, some participants are requested to repeat the experiment for the following two days at a different times.

The above changes ensure that our experimental methodology yields data that mimic realistic driving scenarios in a real car.

Our methodology allows us to test for a number of hypothesis in our experimental data. These include:

1) H0: there is no difference in the holistic comfort perception between occupants in a cabin simulator and those in a real car. This hypothesis will be verified by comparing our experimental data with data from the other four experimental partners.
2) H0: there is no difference between thermal comfort and holistic comfort perceptions in a real car.
3) H0: the relationship between the holistic comfort perception and the set of comfort factors considered can be learned with statistical modelling or machine learning algorithms to give an acceptable predictive error. We aim at achieving an error of 0.5 or less on a comfort scale of 1-9 with 1-point increments.

5.3 Environmental factors

The role of environmental factors is to guarantee comparability and generalisability. For each of them, target level (when not considered as comfort factor) and control or measurement set-up will be described hereafter.

5.3.1 Air temperature

Level:

The target level for air temperature should be set to 22°C. Previously established thermal comfort models highlight the latter as a convenient comfort threshold provided correct values of metabolic rate and clothing applies.

Measurement set-up:

Type K sheeted thermocouples with exposed tip should be implemented in order to monitor the temperature. Type K represents the minimum accuracy required. Type T thermocouples (more accurate) are recommended in case air temperature is considered as experimental factor.

During the set-up phase, temperatures should be measured according to Figure 6 at three different locations: participant's head, trunk and feet. An equal temperatures' readings for the three levels would ensure the uniformity of the air temperature around the participant's body.

During the jury experiment, in case of steady state, a controlled measure of the air temperature has to be assessed with regular frequency guaranteeing the control of this factor. A control Type K (or T) thermocouple should therefore be installed for this purpose.

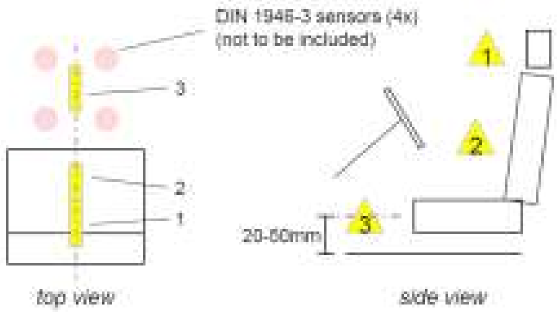


Figure 6: Sensor position (same as OPTEMUS project)

5.3.2 Radiation

Level:

The baseline for thermal radiation should be a setting, in which all enclosing walls are (approximately) at air temperature, and no additional sources of radiation are present. In particular, there is no window to the ambient, and no sun shining into the room. Furthermore, there are no heated or cooled surfaces, except for minor, negligible impacts like a small incandescent bulb. In the baseline setting the radiative heat exchange with the participant is, therefore, limited to the walls and mean radiant temperature is (approximately) equal to the air temperature.

Measurement set-up:

A common concept to quantify radiation is the mean radiant temperature. To determine the mean radiant temperature, a globe temperature sensor is used. The mean radiant temperature is defined as a uniform temperature of an imaginary enclosure, in which radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure [ISO 7726]. As described in ISO 7726 standard, Annex B, a globe temperature sensor consists of a black-coated hollow sphere with a temperature sensor measuring the globe temperature in its middle. The globe diameter can be chosen freely: for a larger globe, the measurement becomes more exact, but gets also more sluggish. The idea of this measurement is that the temperature inside the sphere is a result of convectional heat transfer (air flows around the globe) and radiative heat transfer (radiative heat exchange between globe and environment). If central parameters (air temperature, air velocity) are known, the radiation temperature can be calculated. ISO 7726 also gives the equation for $\overline{T_r} = f(T_{Gl}, v_{air}, T_{air})$ with known globe diameter and known globe emissivity.

This means that globe temperature sensors can be built by any member of the consortium. A common thermocouple temperature sensor can be taken with a table tennis ball attached to its top. Then, the table tennis ball is spray-coloured frosted black to establish an emissivity close to 1.0. The measured temperature inside the table tennis ball is the globe temperature.

5.3.3 Relative humidity

Level:

High and low values of relative humidity can provoke physiological changes (high: sweating, low: mucous changes). Many thermal models include relative humidity as factor (e.g. PMV, ASHRAE-55). As highlighted in priority factors list described in D1.1, sweating is an effective body heat loss mechanism where steam is released from the skin. At high relative humidity ambient levels, the air that surround the body has reached the maximum amount of water vapour and it cannot receive more vapour, so the body evaporation and therefore its heat loss decreases. On the other hand, very dry environments (Relative humidity < 20-30%) are also uncomfortable because of their effect on the mucous membranes.

To evaluate correctly the thermal comfort is important estimate the humidity. Partners agreed to use the recommended level of indoor humidity, ranging between 30 and 60%, as target level for their study.

Measurement set-up:

As the baseline is rather wide, this factor mainly has to be monitored in order to ensure that the relative humidity of the experimental room does not cross the minimum and maximum thresholds. This should be done by measuring regularly the relative humidity. Actions should be taken if the measurements approach the thresholds (if possible – control of relative humidity, postpone experimentation).

5.3.4 Air velocity

Level:

Following Hucho (2008), Schwab (1994), and Fanger (1970) the target baseline value of any studies for air velocity should be under 0.1 m/s to avoid an effect on thermal sensation. After discussing these findings in the consortium in an expert workshop with the partners TME, IDIADA, CRF, ViF, COV and ika, this 0.1 m/s was considered a target threshold. However, the air velocity cannot be fully controlled in an artificial environment, due to the working method of thermal chambers, where most of the studies were being deducted. Following the mentioned expert discussion on these findings, a small deviation from this target value with a hard threshold of 0.3 m/s was considered as acceptable. If the air velocity is under 0.3 m/s for any experiment conducted, the influence of air velocity on thermal sensation can be assumed as not relevant and therefore be neglected. If the air velocity arriving at the participants' skin exceeds this threshold of 0.3 m/s, the influence cannot be neglected and has to be taken into account.

Measurement set-up:

An anemometer (air velocity transmitter) should be used to measure the air velocity at the three positions head, trunk and feet. As shown in Figure 6, it is possible to sufficiently measure air velocity with these three positions.

5.3.5 Air quality - CO2 concentration

Level:

CO2 is a factor that is being monitored only and no attempt was made during experiments to control CO2 levels. However, it can reasonably be expected that indoor CO2 levels will be between 1000 to 2000 ppm. Even if only monitored, it has been deemed appropriate to study its effect in the holistic comfort perception. Should it prove itself to be a very significant parameter, it would be included amongst the suggested development lines to explore, at the project conclusion.

Measurement set-up:

During each experiment, CO2 is monitored using a set of 3 CO2 sensors. The sensors – NDIR (non-dispersive infrared) carbon dioxide (B-530) sensors are manufactured in South Korea by ELT Sensor Corp. The sensors are powered with 12V and provide an output that varies linearly between 0.5 and 4.5V depending on the CO2 level detected. The sensors are factory calibrated and so the use of 3 separate sensors provides some confidence in any individual reading.

Picture 2: CO2 sensor

5.3.6Sound type

Level:

To represent a naturally occurring electric vehicle sound that may impact the experience of comfort, the sound of a Tesla Model was recorded (see Picture 3).

Picture 3: Electric Vehicle (Tesla) for which sounds were recorded

Measurement and Control set-up:

Recordings were made using a bi-aural microphone positioned at ear-height of the passenger seat using an artificial head. During the recording the vehicles were driven at a constant speed of 100km/h. The measured sound pressure level was 64 dBA. Participants listened to the sounds on a Sennheiser HD25-1 headset. As shown in the figure below, three measures for ensuring hygiene were used. First, wipes were used to clean the headset after and before each use. Secondly, disinfecting wipes were used. Alternatively, some partners used disposable headset covers.

Figure 7: Measures used to ensure hygiene

Volume settings:

To set the reproduced sound to the desired sound level, following procedure was used. The microphone of the SPL-meter was pressed between the two cushions of the headset to get the microphone as close as possible to the sound source without creating additional sounds. Then the sound was played for about 5 seconds after which the sound was adjusted so that the SPL on the SPL-meter read 64 dB (A).

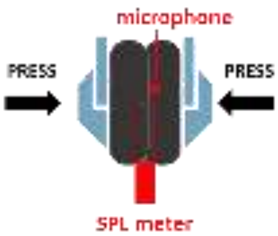


Figure 8: Set-up for measuring headphone loudness

5.3.7Task

Level:

To enhance the realism of measuring comfort in a realistic environment, participants were asked to complete a task. Specifically, participants had to complete the Mobile Tracking Task (MTT) that consists of balancing a tablet such that a graphical disc is kept in the centre of the display, see Picture 4 (ISO, 2012).

Picture 4: Used Implementation of the mobile tracking task

Measurement and Control set-up:
Participants held the display in their hands. The difficulty levels for the MTT were set to the following parameters:

Table 4: Used MTT Parameter Settings

Parameter	Level
Sensitivity	15
Instability	10

Individual participant task load was also measured by questionnaire (i.e. NASA TLX – see 5.5.3).

5.3.8 Experimental space and seating type

Level:
Standard automotive seat should be implemented throughout the experimentation. They contribute to standardize the posture of participants and ensure the minimum required contextualization of a driving environment. When possible, partners are encouraged to set up additional automotive elements such as steering wheel or door panels. When possible, a vehicle cabin should be used to convey a context closer to reality.

Set-up:
This factor is ensured by a proper construction of each partner’s experimental set-up. Notably, seating comfort will be assessed for each test case via a questionnaire.

5.3.9 Lighting of experimental space (illuminance, colour, presence of ambient light)

Level:
Fix parameters for the illumination of the environment in which the experimentation takes place have to be taken into account:

- Light intensity should be set equal to 800 lux.
- Light colour should be chosen on a predetermined range set between 3000 K and 4000 K of the colour Kelvin scale, resulting in a clear neutral white illumination.

Measurement set-up:
The following measurement set-up and control points were suggested in order to ensure a consistent lighting across study locations.

- Check set-up before experimentation using a lux meter (recommended - e.g. Dr.Meter LX1010B) or with a free smartphone app. Relevant of the light intensity should be taken with a lux meter (for instance Dr.Meter LX1010B). As an alternative a smartphone app is considered acceptable. Measurements must be taken at the level of participant's eye and the reading should not be superior to 800 lux.

- The colour of the room light is ensured by the experimental set-up: room equipped with white light sources (e.g. neon, LED, light bulbs).
- Additional (coloured) sources of light (e.g. car's dashboard retro illumination, distracting light sources, and screens) have to be avoided or obscured when possible. Attention has to be paid to carefully avoid direct illumination in the eyes of participants. Exceptions are made for experimentations using a driving simulator (i.e. light from the driving simulator itself).

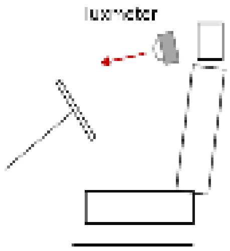


Figure 9: Set-up for position of lux meter

5.3.10 Ambient scent

Level:

In order to have a baseline scent across location it was decided to use the same deodorizer across test location.

Control set-up:

Pilot test with 5 "Neutral" deodorizers were conducted. The one perceived as most neutral was selected. It corresponds to the "Envii Bed Fresh" deodorizer. The deodorizer should be sprayed in the cabin (air and surfaces) when participants are not there, in between test cases.

The frequency of application depends on the test location and the experimentation factor:
- If no mid/strong odour source in the room: deodorizer should be sprayed once a day in the experiment room
- If mid/strong odour sources in the room: spray frequency should be increased. This procedure is at discretion of DOMUS partners and may vary across them.
- When ambient scent is an experimental factor: deodorizer should be applied right after the test cases have been undertook (together with other countermeasures such as the ventilation of the space) in order to ensure a neutral scent for the following test.

5.4 Individual factors

5.4.1 Demographic

Level:

Targeted gender distribution should be a 50/50 ratio between male and female. If the latter can't be fulfilled a minimum ratio of 3/8 between the least representative gender should be ensured.
Furthermore, at least 70% of the total number of the participants should be between 20 and 70 years old.

Measurement:

This factor should be controlled by pre-screening the participants before the experimentation and distributing test cases to them according to the conditions previously defined.
The following demographic information were asked to the participants: age, gender, height and weight (also allowing the calculation of body mass index). They cover the priority factors influencing comfort identified in D1.1 and related to demographics.

5.4.2 Clothing

Level:

The baseline clothing should be composed by a pair of trousers or jeans (0.24 clo), a long-sleeve shirt (0.25 clo), shoes (0.02 clo) and underwear (approx. 0.10 clo). The clothing calculation is finalized with the implementation of the car seat, which, for the DOMUS scope, replicates the role of an executive chair (0.15 clo, in accordance to the ISO standards). The total adds up to 0.76 clo.

Measurement:

- In order to fulfil the clothing requirement, prior to the experimentation phase, volunteering participants should be asked to wear the necessary clothes. In case of oblivion, each partner commits to provide the necessary garb.
- At partner's level eventual installation of changing room could be implemented. The change of clothes should happen prior to the experimentation phase.
- A tolerance of +/- 0.1 Clo (e.g. T-shirt, thinner trousers) is accepted. In this situation. partners should ask and calculate the corresponding clothing level. The value should be reported in the appropriate space of the moderator sheet. For a better track of participant's appeal, the moderator sheet is provided with a table on which the exact clothing variable can be correctly quantified (see below).

Table 5: Clo values and their measurement

Garment description	I_{cl} (clo)	Garment description	I_{cl} (clo)
Underwear		**Dresses and skirts**	
Bra	0.01	Skirt (thin)	0.14
Panties	0.03	Skirt (thick)	0.23
Men's briefs	0.04	Sleeveless, scoop neck (thin)	0.23
T-shirt	0.08	Sleeveless, scoop neck (thick), i.e., jumper	0.27
Half-slip	0.14	Short-sleeve shirtdress (thin)	0.29
Long underwear bottoms	0.15	Long-sleeve shirtdress (thin)	0.33
Full slip	0.16	Long-sleeve shirtdress (thick)	0.47
Long underwear top	0.20		
Footwear		**Sweaters**	
Ankle length athletic socks	0.02	Sleeveless vest (thin)	0.13
Pantyhose/stockings	0.02	Sleeveless vest (thick)	0.22
Sandals/thongs	0.02	Long-sleeve (thin)	0.25
Shoes	0.02	Long-sleeve (thick)	0.36
Slippers (quilted, pile lined)	0.03		
Calf-length socks	0.03	**Suit jackets and waistcoasts** (lined)	
Knee socks (thick)	0.06	Sleeveless vest (thin)	0.10
Boots	0.10	Sleeveless vest (thick)	0.17
Shirts and blouses		Single-breasted (thin)	0.36
Sleeveless/scoop neck blouse	0.12	Single-breasted (thick)	0.44
Short sleeve knit sport shirt	0.17	Double-breasted (thin)	0.42
Short-sleeve dress shirt	0.19	Double-breasted (thick)	0.48
Long-sleeve dress shirt	0.25		
Long-sleeve flannel shirt	0.34	**Sleepwear and Robes**	
Long-sleeve sweatshirt	0.34	Sleeveless short gown (thin)	0.18
Trousers and coveralls		Sleeveless long gown (thin)	0.20
Short shorts	0.06	Short-sleeve hospital gown	0.31
Walking shorts	0.08	Short-sleeve short robe (thin)	0.34
Straight trousers (thin)	0.15	Short sleeve pajamas (thin)	0.42
Straight trousers (thick)	0.24	Long-sleeve long gown (thick)	0.46
Sweatpants	0.28	Long-sleeve short wrap robe (thick)	0.48
Overalls	0.30	Long-sleeve pajamas (thick)	0.57

5.4.3Thermal history

Measurement:

The idea of including thermal history as a factor comes from the adaptive comfort literature (Nicol et al, 2015). It is based on the observation that survey respondents in hot climates are comfortable at a much hotter temperature than their temperate climate counterparts. In principle, some form of acclimatisation occurs over time, increasing as the duration spent in that environment increases.

Most commonly, adaptive comfort literature uses an exponentially weighted mean of the outdoor temperature from the last 7 days and this is also suggested by Nicol et al. (2015). Specifically, they suggest a recursive form:

$$T_n = (1-\alpha)Z_{n-1} + \alpha T_{n-1}$$

where T_n is the exponentially weighted moving average of the temperature at day n, Z_n is the mean outdoor temperature on day n, $\alpha = 0.8$ is a constant that controls the relative weight of older temperatures. Note that only the last 7 days of outdoor temperatures are used.

5.4.4 Metabolic rate

Level:

The metabolic rate during the experimentation phase should be the same across all participants. The value suggested would reflect the amount of physical activity of a person when driving. The ISO/DIS-14505 part 1 indicates a range of 70 to 90 W/m^2 of energy consumed when conducting a vehicle in different situations. The range corresponds to a 1.2 to 1.6 MET equivalent. For the experimentation a metabolic rate of 1.2 MET should be considered as it represents the energy dissipation of driving on paved roads. According to ISO 7730, the latter also corresponds to the heat production of a person performing a sedentary activity (e.g. office, dwelling, school, and laboratory).

Measurement:

The 1.2 MET should be replicated with the implementation of a task that ensure the same level of metabolic rate (see 5.2.8). Attention has to be given on participant's physical activity 30 minutes prior to experimentation (recorded on questionnaire).

5.4.5 Thermal sensitivity

Level:

No level was established for this individual factor. It should be controlled with the questionnaire described below.

Measurement:

Individual thermal sensitivity and preferences towards a colder or warmer environment manifest themselves in warmth or cold-seeking behaviour (Yoon et al., 2015, Van Someren et al., 2016). Van Someren et al. (2016) based a questionnaire on the retrospective reporting of these behaviours and subjective preferences. N = 240 participants formed the databases for the development of the questionnaire resulting in 21 dimensions assessed on a 7-point bi-directional Likert scale. Seven relevant items were identified and adapted. One item assesses the general preference of cold or warm temperatures, four items the adaptability of how fast the body adapts to cold or warm environments, and two items on physical activity and its effect on the heating or cooling of the body. Based on the earlier mentioned workshop with relevant partners in Munich, all relevant dimensions of the proposed questionnaire by Someren et al. (2016) were covert with this approach.

5.4.6 Acoustic sensitivity

Level:

No level was established for this individual factor. It should be controlled with the questionnaire described below.

Measurement:

Acoustic sensitivity is measured via the Weinstein´s Noise Sensitivity Scale (Weinstein, 1978; Worthington & Bodie, 2017). This scale contains 21 items and it is rated on a 6-point scale (from "strongly disagree" to "strongly agree"). The items express attitudes toward noise in general and emotional reactions to a variety of environmental sounds encountered in the everyday life. A higher score in this scale indicates higher noise sensitivity of the participant. Both reliability (internal consistency: α =.85; test re-test reliability: r_{tt}= .87.) and validity of the German version are satisfactory (Zimmer & Ellermeier, 1997). All 21 items of the scale are presented in "14. Appendix B – Questionnaire A". For studies not considering sound as an experimental variable, it was agreed to shorten the questionnaire to the most representative items (i.e. items 7, 8, 18, 19, 21).

5.5 Dependent variables

In this section the dependent measures are detailed. The relevant questionnaires for the later reported studies will be described. These questionnaires were identified as relevant by the involved partners in a workshop in Munich and several teleconferences. The application of these questionnaires will be described in “5.6 Procedure” (p.38). All questionnaires discussed among partners were in English. When possible, it was suggested to translate the questionnaires into the local language before handing them out to the participants.

5.5.1Thermal sensation

The thermal sensation scale corresponds to the ISO sensation scale (ISO14505-3). Standard scales ensure replicability, as results can be compared directly with International standards assessments as well as with the results of other studies. “Please rate on these scales how you fell NOW” is presented to participants. The emphasis to the subject is how the person feel (how he/she actually feels and not how the environment is perceived) at the moment in which the question is asked (a.k.a. read). The form of the scale is in discrete interval described in 7 steps: from cold [-3] to hot [+3].

A five-item table is presented. Participants record their overall sensation as well as their sensation at head, trunk- rear, trunk- back and feet level.

5.5.2Comfort appreciations

Sensory comfort and overall comfort

To determine the subjective acoustic discomfort of the participants regarding the EV sounds, a magnitude estimation method with cross-modality matching is applied (Stevens & Marks, 1980). That is, the participants are asked to indicate how annoying the sound was by writing down a number and drawing a straight line which indicate the level of the subjective acoustical discomfort. A higher number and a longer line indicate more acoustic discomfort. The participants do not get any anchor value, such that they rate their subjective annoyance based on an internal scale. In order to use this method properly, the participants need an initial training phase before the experimental trials start. Furthermore, after the end of the experiment, this method requires that the participants assign given verbal qualifiers (e.g., ‘good’, ‘bad’, ‘very good’ etc.) to the magnitude estimation responses they provided during the experiment. In this way, it is possible to provide a linguistic interpretation to the number/line preferences about the perceived acoustic discomfort in the simulated vehicle.

Time to discomfort

Furthermore, the time to holistic discomfort is addressed with the following question: “*Considering all comfort elements, how many minutes do you think it would take you until experiencing the ride as uncomfortable?”*

5.5.3Task load

The task load is measured via the NASA TLX (1986; see also 16 Appendix D – Questionnaire C). The NASA TLX is a standard measure to assess the overall workload on based six subscales: Mental demands, physical demands, temporal demands, performance, effort, and frustration. Each item is rated based on a 20-point rating scale from “low” to “high”.

5.6 Procedure

5.6.1Flow

The individual questionnaires described in the previous sections (to measure factors value or to collect dependant variables) were organised in three clusters: questionnaire A (QA), questionnaire B (QB) and questionnaire C (QC). They have been included as reference in the appendices (sections 14 to 16). The protocol flow is represented on Figure 10 with each item described below.

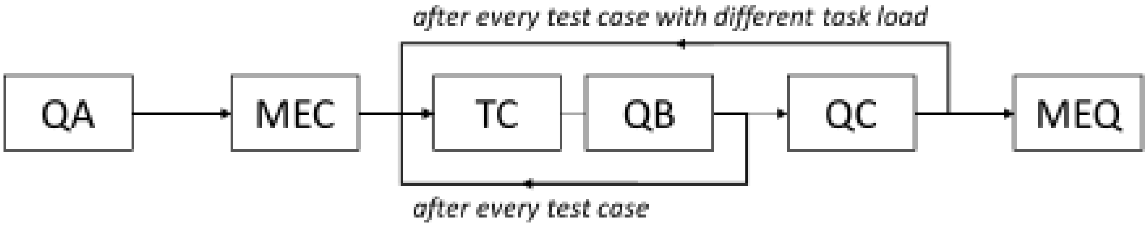


Figure 10: Experimental protocol overview

QA consisted in the collection of participants' demographical data, temperature and activity history as well as noise and thermal sensitivity.

MEC consisted in the calibration phase of the magnitude estimation method (Stevens & Marks, 1980). It allowed them to understand and familiarize with the unusual format of this method.

TC represent the moment participants experienced a specific test case in a car cabin. In accordance with ISO 14505-3 standard, a minimum of 8 participants were required for each test case presented (minimum acceptable sample size). Each test case consisted of a period during which participants were instructed to perform a task on a tablet while listening to an EV car noise through a headset. Before each test case, when participants were not yet in the vehicle, the experimenter set the environment of the cabin to correspond to the next test case planned. Questionnaire B were distributed at the beginning of each test case.

QB consisted in the evaluation of the test case experienced. It was filled in the cabin and is composed of three sections. The first section focused on thermal sensation. The second section consisted in a question regarding time to discomfort. The final section consisted in a comfort assessment of five sensory components (thermal, acoustic, seating, visual environments, and seating) as well as overall comfort using the magnitude estimation method (Stevens & Marks, 1980).

QC consisted in an evaluation of the task using the NASA Task Load Index (1986).

MEQ consisted in the qualification phase of the magnitude estimation method (Stevens & Marks, 1980).

The choice was left to each partner to investigate its experimental factors as between subject variable or as within subject variables. When treated as within subject variable different values of the factors would be tested by a single participant using the loop back described on Figure 10. When treated as between subject variable the factor value was kept constant for all the test cases experienced by a single participant (due to the time needed to stabilize at a constant value, air temperature was often treated as such).

5.6.2 Data collection

The aligned measurement set-up for each factor have been described in 5.3. The suggested approach is to conduct the jury evaluations in a controlled environment in order not to have to measure each factor at all time.

Control sensors (such as for air temperature or C02 concentration of the cabin) should nevertheless be kept at all time during the jury experiment as long as their presence does not interfere with the comfort perception of the participants. The value of the control sensors can be acquired digitally or manually via the moderator sheet (distributed to partners as part of the experimentation package).
Questionnaire should be administrated according to the protocol described in section 5.6.1. These questionnaires can be either distributed by paper, voice or electronically (decision at partner level).
All the data (sensor, set-up, questionnaire) that have been collected such been shared with Coventry University (partner in charge of the mathematical modelling) using a standard format (i.e. "DOMUS Data output.xlsx") that has been distributed to partners prior to experimentation as part of the experimentation package.

6 Individual study methods & initial findings

6.1 COV study – naturalistic study

6.1.1 Introduction

COV experiments considered air temperature, radiant temperature, airflow speed, sound and ambient scent as experimental factors. They took place daily between 22nd and 25th July 2019 inclusive. During the experimentation 10 participants were exposed to test cases with a choice from one of three different scents (including "neutral" as baseline) in a Citroen C3 parked in an outdoor parking bay at Coventry University and oriented ENE (0600).

6.1.2 Experimental factors

Ambient scent

A preliminary pilot-test has been set up in order to identify potential scents that could be implemented in the DOMUS experimentation. The aim is to understand whether a scent can enhance a sensation of comfort or, on the contrary, spoil it. The experiment is conducted for a period of 20 minutes. Before the session one VAVA Car Diffuser is filled with 12 droplets of essential oil added to 60 ml of water and introduced into the vehicle.

The diffuser of choice is turned on at the start of the session and the scent is released into the vehicle cabin. Three minutes after activation, participants are invited to fill in a questionnaire.

Peppermint and orange & cinnamon have been identified as scents with the potential to provide a warm and cold sensation. They have therefore been included as scents to be tested in the COV experimentation.

Air temperature

Temperature is controlled by the participant in an attempt to adjust the vehicle cabin conditions for optimal comfort. The participant can switch the fan on with eight different speed settings and can control the direction of airflow from one of three sources, demister (front windscreen), torso (panel) and feet. The values selected range from "low" (below 14^0C) and from 14^0C in increments of 0.5 degrees up to 30^0C or "high".

Radiant temperature

Radiant temperature is measured at the head torso and feet locations and logged throughout the experimental sessions for each participant using a globe sensor constructed from a type K glass braid insulated thermocouple encased in a table tennis ball coated with black spray paint.

Airflow speed

Airflow speed is measured and logged at the head torso and feet locations and logged throughout the experimental sessions for each participant using a compact anemometer.

Sound

Sound is provided to simulate an electric vehicle using the "Tesla_100kph. [Left][Right].mp3"sound file played back from a tablet device with the participant listening on headphones.

6.1.3 Set-up description

Air temperature

Before jury experimentation, the vehicle was locked, with the ignition switched off. Temperature was measured at the three locations (head, trunk, feet) indicated in previous section. During jury experimentation the vehicle was equipped with three type T thermocouples located alongside the driver's right and resting on the seat and headrest of the passenger seat. Internal temperature measures are recorded throughout each test case using DHT22 temperature-humidity sensors. Outside test hours, the car has been switched off with the windows fully closed. This was for security reasons to discourage theft of equipment from the vehicle during the day and theft of the vehicle overnight. Five (5) minutes prior to beginning of tests the car has been switched on with the HVAC switched off.

Air velocity

Air velocity has been measured during the tests for the three different body parts. In order to check air velocity level a "Wind Sensor Rev C" compact anemometer has been utilized. Measurements of air velocity at feet, trunk and head level were taken at intervals throughout the experiments.

Sound type

According to general protocol, the "Tesla_100kph. [Left][Right].mp3"sound file has been exploited. For COV the "Decibel X Pro Noise Meter" has been utilized to ensure a maximum of 64 dB(A) as sound level output from Sennheiser HD 25 Basic Edition headphones, also utilized in the TME experiment as recommended.

Task

Tablet iPad Mini 2 was provided at the beginning of each test case with the aforementioned headset. Mobile Tracking Task in agreement with the general protocol have been utilized. After two minutes task duration, a recorded voice invite participant to stop the task. Participants were then invited to leave the tablet on the passenger seat while filling the questionnaire in the car.

Experimental space and seating type

The experiment has been carried out in a parking bay of the open-air car park at Coventry University's Future's Institute. During the sessions, a Citroen C3 has been parked in the space and not moved during or between experiments. During the sessions both cars have been kept with the engine running at 1000 rpm and the engine was revved to 3000rpm for one minute in between sessions to keep the auxiliary battery charged.

Lighting (illuminance and presence of ambient light)

The vehicle has been illuminated with natural light, measured every five minutes at the participants' eyelines inside the vehicle using a hand-held digital LUX meter, model LX1330B, pointing away from the participants' faces.

Ambient scent

VAVA aroma diffusers model VA-AD008 were filled with one each of two scents: orange & cinnamon and peppermint. Concentration of mixture reflects the ones of the pilot test: 12 droplets for 60 ml of water. The box proved necessary in order to nullify problems of leakage and avoiding possibilities of overturning diffusers by the experimenter. Furthermore, the presence of both scent diffusers guaranteed a faster set up of the new in-cabin condition for the following test case.
In order to reset the car environment in-between test cases, the doors of the vehicle were opened, and any scent dispersing equipment removed. If participants requested a neutral odour, an odour neutralizer has been sprayed in the cabin or into one of the scent diffusers (as suggested - Envii Bed Fresh).

Participant's demographics

The jury panel was made up of 10 people, 8 male and 2 female subjects, whose age distribution is shown in the following table.

Table 6: Age distribution on COV experimentations

age class	frequency	%
<30	8	80%
30-39		%
40-49		%
50-59	2	20%

>=60		%

Participant's clothing

Participants arrived wearing their clothes of choice and an assessment was made of their cumulative Clo value from the scale of the Fanger comfort model.

Participant's heart rate

Heart rate was measured and recorded every five minutes using an Apple watch strapped to the participant's wrist.

6.1.4 Protocol Specificities

The COV protocol is illustrated in the figure below. Like the DOMUS experimental methodology, our experimental methodology investigates the influence of all comfort factors given in Table 1 on holistic comfort perception. However, our methodology is aimed at obtaining experimental data from a real car environment (rather than a cabin simulator) and to replicate realistic user behaviour, in order to validate the holistic comfort model built on the data from the other four experimental partners. Hence, our methodology differs in a number of ways from the broader DOMUS experimental methodology:

6) Our experiments are conducted in a real car in a parking lot, as opposed to a cabin simulator.
7) The non-traditional comfort factors are not varied intentionally by the experimenter.
8) The environment is not controlled, and hence the baseline values are not guaranteed to be met.
9) Participants are not tested for any test cases. Instead, the ambient environment is allowed to change naturally, while the cabin occupant is encouraged to make changes to the HVAC settings to feel comfortable. Measurements of the comfort factors are carried out immediately the participant enters the car, and it is repeated every 3 minutes – after which the participant indicates their holistic comfort perception – for up to 30 minutes.
10) In order to introduce variability in the data, the participant adjourns to retake the experiment for the following two days at a different time.

The above changes ensure that our experimental methodology yields data that reflect realistic driving scenarios in a real car.

Table 7: Comfort factors and their measurement

Comfort factors	**Measurement information**
Air temperature	Measured at the head, trunk and feet
Radiant temperature	Measured at the head, trunk and feet
Airflow speed	Measured at the head, trunk and feet
Sound type	Electric vehicle noise at constant speed
Illuminance	Measured in front of the head at the passenger's eyeline
Scent type	N/A
Activity Task	Measured by Questionnaire C (See appendix D)
Met level	Estimated by heartbeat rate
Temperature/ activity history	Measure by Questionnaire A (See appendix A)
Participant demographic information (e.g., age, sex, height, weight, temperature/noise sensitivity)	Measured by Questionnaire A (See appendix A)

After entering the vehicle, participants undertake a magnitude estimation calibration procedure and, at five-minute intervals, answer questionnaires A, B and C. The test case takes place in the car, at the end of which a final questionnaire is presented to establish a reference for verbal qualifier statements.

Before QA (Clo value and consent form)

When joining the experimentation all participants read and signed an agreement consent form for the collection of personal data prepared with the support of COV legal department. The calculation of the cumulative Clo value was estimated by one of the experiments' moderators using the table presented in section 5.4.2 ("Clothing") so as not to have the participants list the exact clothing or undergarments that they were wearing on the day. Participants are welcomed inside the vehicle and shown the various controls for the HVAC. Questionnaires A, B and C are presented electronically on an iPad tablet.

6.1.5Test case

Participants entered the car to experience the test case with the tablet questionnaire and were left in autonomy for 3 to 5 minutes between each round of answering the same questions.

Between test cases

Participants exited the car and were dismissed. The experimenter reset the environment and awaited the next participant, sometimes within a few minutes and sometimes after a few hours. In all cases the environment was considered to be fully reset before starting the next test case.

6.1.6Set-up and protocol specificities

The experimental tests were carried out in a Citroen C3 powered by an internal combustion engine, parked in an open-air parking space on the university's grounds.

Measurements inside the cabin of the Citroen C3 were taken with the following instrumentation:

1) COV-built measuring equipment (Picture 5). The head and torso are simulated by the median and upper measuring equipment on the white trunking conduit.
2) Arduino experimental prototyping board and SD card for data acquisition and processing.

Picture 5: Experimental sensing and measuring equipment

The measuring equipment was placed to the right of the front passenger seat, extending from the foot well to the headrest, where the subjects taking part in the experimental campaign also sat.

The air temperature, radiant temperature and air flow speed were continuously measured.

6.1.7 Relevant findings

Some data were missing for particular test cases and/or for an individual participant in the magnitude estimation and in the test cases. Consequently, these data have been excluded from any further analysis which has reduced the sample size.

Comfort scores

Before the subjective tests were carried out, participants were engaged in a magnitude-estimation exercise to prepare them for scoring the values in six comfort dimensions; thermal, acoustic, seating, visual, olfactory and overall comfort. There was a lot of variation in the numbers and line lengths estimated by participants in this magnitude-estimation qualification which would need to be normalised in order for the recorded values to have meaning when all of the participants' data is compared. That is, one participant's score of 30 might relate to slightly bad whereas another may have used 40 for terrible. These data are given in Figure 11 and 12. Values for participant 2 are missing from the collected data.

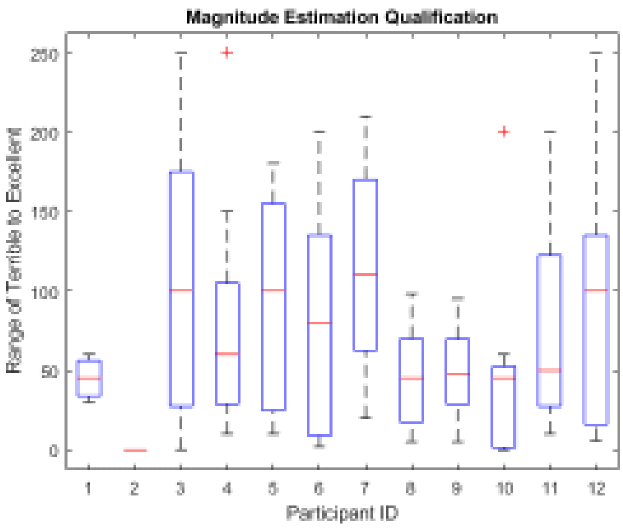


Figure 11: Distribution of magnitude estimates numbers given by each participant

During the subjective test, participants evaluated their overall and thermal comfort, whilst cabin temperature measurements were recorded for the following:

- Head
- Trunk
- Feet

Temperatures

The experiments took place over a week in July 2019 during which the hottest ever UK weather in history was recorded at 38.7°C on 25th July 2019. This meant that the HVAC was operating at the extreme and participants were likely to be experiencing some thermal discomfort from the outset, for which they were compensating with the use of vented cooled air from the air conditioning (AC) system. Average outdoor temperatures over the four days of the experiments rose from 18°C to 34°C with a dip for both participant 6 and 9. In most cases, participants used AC to cool down and no case of the outside temperature being cold enough for participants to feel the need to use heating was recorded.

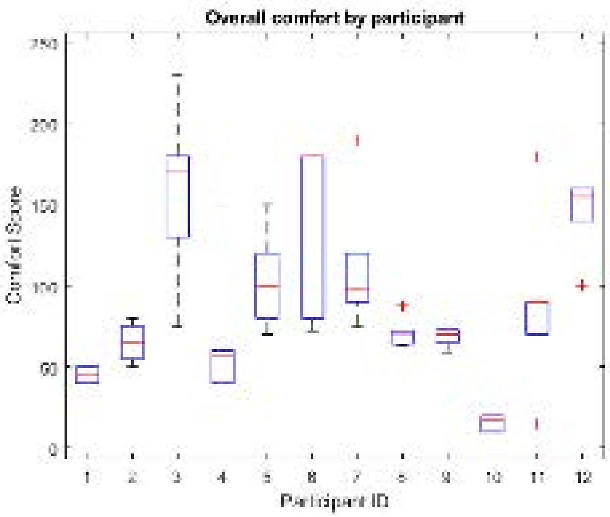


Figure 12: Distribution of overall comfort scores for each participant

Comparing the verbal qualifiers with the magnitude estimation numbers that the participants provided before the experimentation, participants with a wider range of values in the comfort scores tended to have a wider range of values in the verbal qualification of those comfort scores. This could be used to assist in normalising the data for comparison.

The mean outdoor temperatures during the experiments are given below in Figure 13:

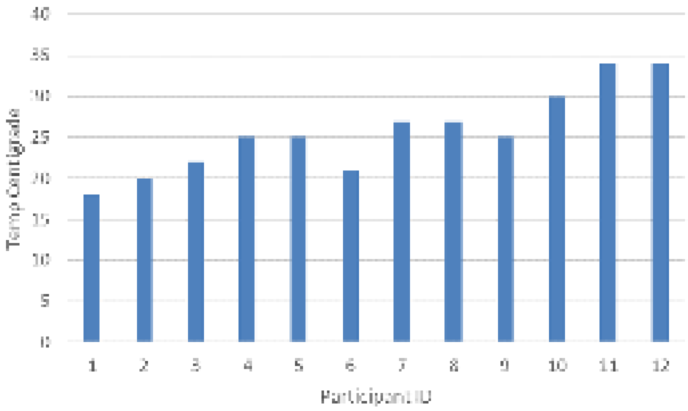


Figure 13: Mean outdoor temperatures during each participant's experiment

Radiant and air temperatures inside the vehicle during the experiments were recorded at the head feet and trunk. Whilst there wasn't huge variation across the three zones, temperatures generally rose, fell or remained constant as a group with similar trends across the three zones, with some participants recording greater temperatures at the head than feet whilst others recorded the lowest temperatures in the head zone. This was true for both ambient and air temperatures. Each vertical group of six from 1 to 71 (that is 1-6, 7-12 etc.) records the different temperatures (3 for air temperature, and 3 for radiant temperature).

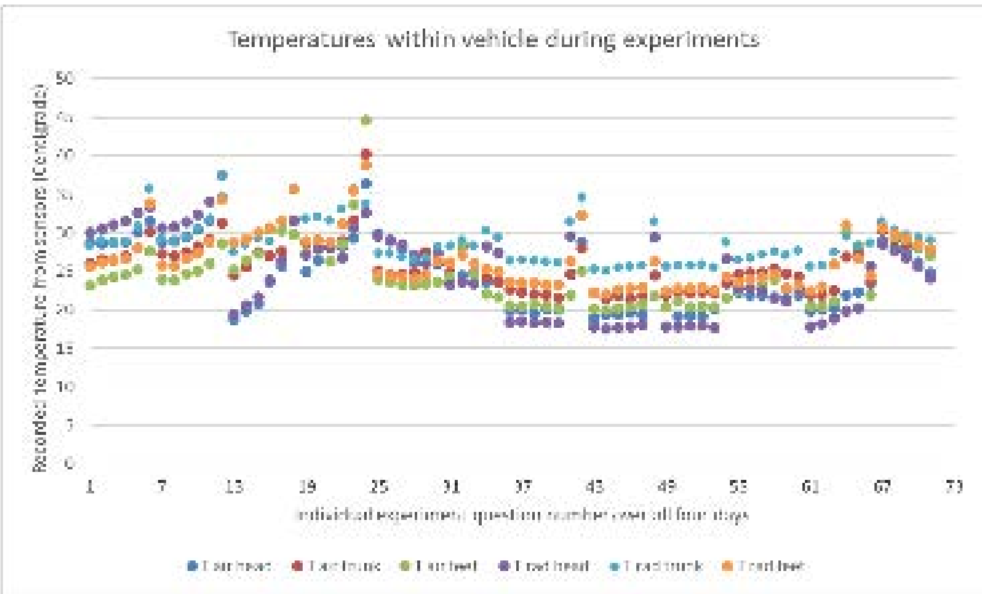


Figure 14: Temperatures recorded inside the vehicle for different test cases

Also shown in Figure 15 is a variation of the temperatures at the three zones (head, trunk and feet) for both air and radiant temperatures.

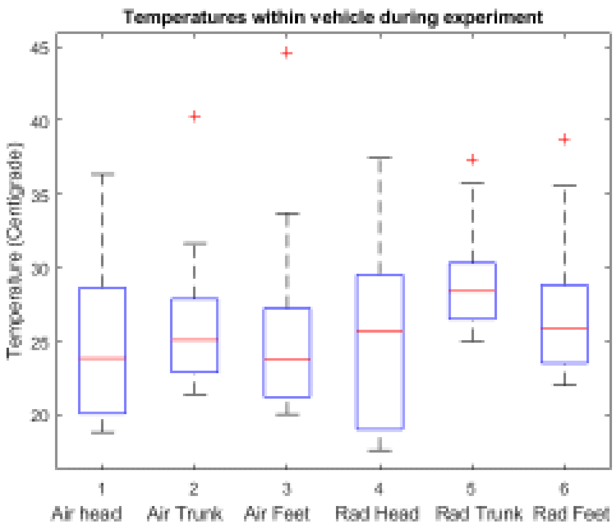


Figure 15: Distribution of temperatures inside the vehicle over four days of experimentation

The correlation between the above cabin temperatures and occupants' thermal comfort is expected to be non-linear, partly because discomfort can be caused by both high and low temperatures. Therefore, a plot of thermal comfort vs temperature is more likely to be U-shaped where discomfort caused by low temperatures moves towards comfort in the mid-range temperatures and then becomes uncomfortable again with much higher temperatures.

Airflow

Airflow measurements taken at the trunk for the last four participants showed a value of 1009, equivalent to an output of 5V from the anemometer, suggesting that the equipment had failed and was producing this unusually high value unrelated to the actual airflow.

Lux levels

Below, in Figure 16, is the distribution of the lux levels during the experiments.

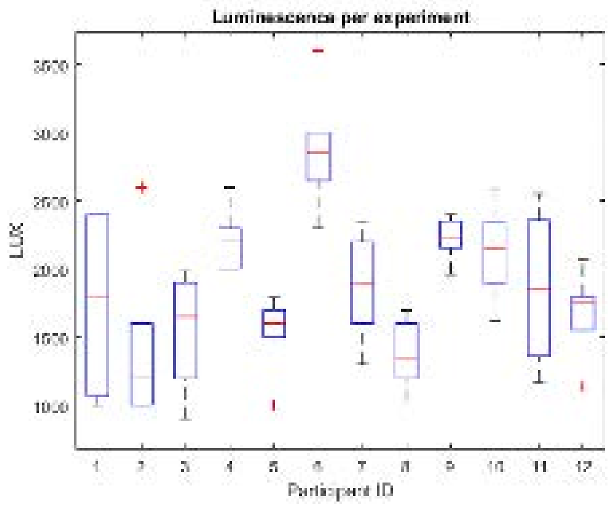


Figure 16: Distribution of luminescence values (LUX) recorded during each participant's experiments

6.1.8 Discussion

Magnitude estimation and the results of survey questions in the COV experiments showed that participants had a wide variety of overall comfort experiences during the experiments compared with any variation between participants' estimation scores suggesting most of the variation in the results came from the experiments and not so much from the individuals.

However, the wide range of magnitude estimation values provided by the participants before the experiments began in earnest indicates a need to consider the different scale of each participant's recorded comfort levels during the experiments. Either before a full analysis of the data, or during the computation of a comfort model, care should be taken to adjust or normalise by a mathematically sound statistical method or process the scores of each individual participant so as to ensure comparing like with like.

By inspection, a plot of the correlation between LUX levels as well as other comfort factors and measures of overall comfort do not show any obvious causal link between the two for these experimental results. This is mainly due to the fact that the comfort scores are subjective, and underscores the need to properly normalise the comfort scores before any such correlations can be drawn.

Since participants could register thermal and overall discomfort at temperatures that are too low just as readily as for temperatures that are too high, this suggests that the shape of the function determining thermal comfort is more likely to be quadratic in nature with increasing comfort values either side of some centrally located optimal temperature.

Finally, only for one participant was the recorded outdoor temperature lower than 20^{o}C during the experimentation and fewer than 10% of the recorded in-cabin temperatures were less than 20^{o}C, meaning that the thermal comfort perception of participants in more than 90% of cases was based on a range of temperatures that were all above what might be considered to be cold and therefore most of the useful data relates to warmer conditions.

6.2 CRF study – asymmetrical thermal environment

6.2.1Test cases

The experimental campaign carried out at the FCA laboratories by CRF in the frame of the work planned for *Task 1.2 Holistic model of passenger comfort* aimed at establishing the influence of an asymmetrical thermal environment on the thermal comfort perception of the passenger.
The experimental protocol included both subjective and objective testing.

The subjective testing campaign was executed complying with the common experimental procedure shared among the work team of Task 1.2 and described the sections above (previously in the document *T1.2 Experimentation overview flow and guidelines*); three parameters were made to change during the testing session, namely

- Outlet positions
- Vent blower velocity
- Sun radiation

as described in the following paragraph.

The jury panel was made up by thirty-one people, 19 male and 12 female subjects, whose age distribution is shown in the following table.

Table 8: Age distribution on CRF experimentations

age class	frequency
<30	2
30-39	7
40-49	12
50-59	8
>=60	2

Four moderators assisted in the testing, each one having a background in psychology or statistical science.

Thermal dissymmetry subjective test

The subjective testing was carried out in the following boundary conditions:

- Temp. ambient = 22°C
- Humidity = constant 20%

Moreover, it was comprised of the test phases described below:

0. dashboard outlets in neutral position, get into the vehicle + subjective rating
1. reach the comfort at 22°C (A/C on; HVAC mixer handle in middle position (neutral position); blower handle in 1 position; air distribution in dashboard outlets; personal moving of the dashboard vents) + subjective rating after 5 minutes
2. move the dashboard outlets in neutral position, lateral sun simulator switching on + subjective rating after 10 minutes
3. personal moving of the dashboard vents + subjective rating after 5 minutes
4. move the lamp away, dashboard outlets in neutral position + subjective rating after 5 minutes

5/6. close the central right outlet, set the blower at medium and maximum air velocity (3 and 4 blower handle positions) with the lateral right outlet in neutral position + subjective rating for each air velocity (after 5 minutes for each one)

7. additional phase: open the central outlet and personal moving of it and the lateral one; personal selection of both the air velocity and the temperature (using the mixer and blower handles), then subjective rating after 5 minutes
8. test end

The total time for one test was approximately 40 minutes. The experimented test cases are summarized in Table 9.

Table 9: CRF test cases overview

Test case ID	Vents	Open / Close	Environmental factors				
			T_{AIR} [°C]	Irradiation [W/mq]	HVAC blower knob position	Vents position	
0	Central	Open	22	0	1	Neutral	evaluation at ingress in car
	Lateral	Open					
1	Central	Open	22	0	1	Personal moving	evaluation 5 min after setting
	Lateral	Open					
2	Central	Open	22	500	1	Neutral	evaluation 10 min after setting
	Lateral	Open					
3	Central	Open	22	500	1	Personal moving	evaluation 5 min after setting
	Lateral	Open					
4	Central	Open	22	0	1	Neutral	evaluation 5 min after setting
	Lateral	Open					
5	Central	Close	22	0	3	Neutral	evaluation 5 min after setting
	Lateral	Open					
6	Central	Close	22	0	4	Neutral	evaluation 5 min after setting
	Lateral	Open					
7	Central	Open	22	0	Personal setting	Personal moving	evaluation 5 min after setting
	Lateral	Open					

6.2.2Set-up and protocol specificities

The experimental tests were carried out in a Fiat 500 powered by an internal combustion engine, placed in a climatic chamber 7.6 m long and 5.0 m wide, which temperature can be adjusted in a range from -30°C to +55°C and which was kept at 22° C constant temperature.

The accuracy of the chamber setting is ±1°C for the temperature and ±5% for the relative humidity when operating with a vehicle at running engine, as it was the case.

The sound level inside the passenger compartment of the Fiat 500 placed in the climatic chamber was measured with the following instrumentation commonly used for acoustic detection:

1) Brüel & Kjær's head / torso simulator (Picture 6).

The head and torso simulate the presence of the human body inside the vehicle, the head featuring two microphones at the ears.

2) Siemens Mobile multi-channel data acquisition system used to acquire acoustic head microphones.

3) Laptop for data acquisition and processing.

Picture 6: Brüel & Kjær's head / torso simulator

The Brüel & Kjær's manikin was placed on the front passenger seat, where the subjects taking part in the experimental campaign also sit.

The ambient noise at several climatic chamber and vehicle configurations was measured:

- still climatic chamber and vehicle doors open – engine off
- still climatic chamber and vehicle doors closed – engine off
- operative climatic chamber and vehicle doors closed – engine off
- operative climatic chamber and vehicle doors closed – engine on and HVAC at level 1
- operative climatic chamber and vehicle doors closed – engine on and HVAC at level 4

Results are shown in the following figures:

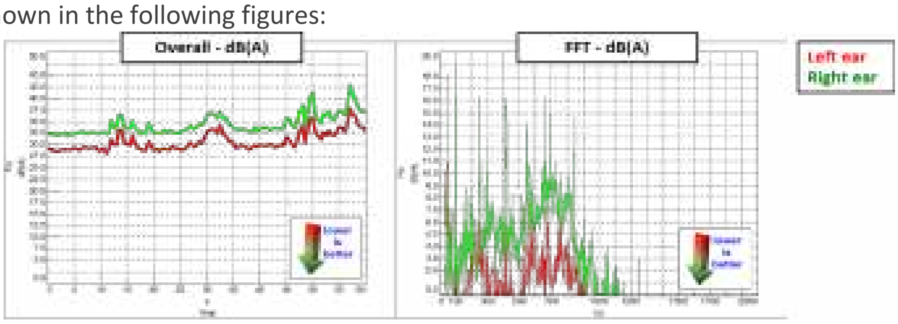


Figure 17: Still climatic chamber and vehicle doors open – engine off

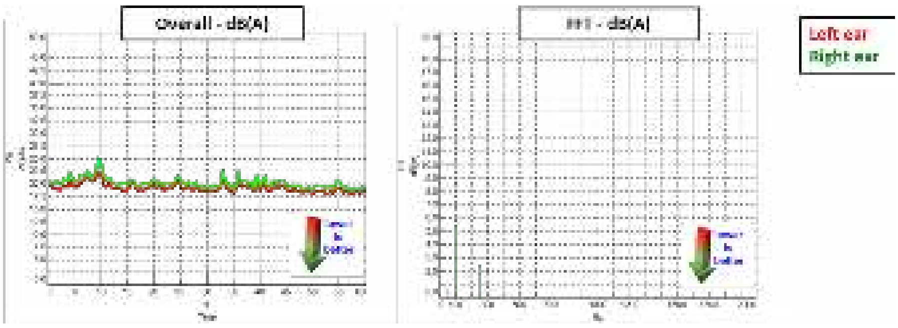


Figure 18: Still climatic chamber and vehicle doors closed – engine off

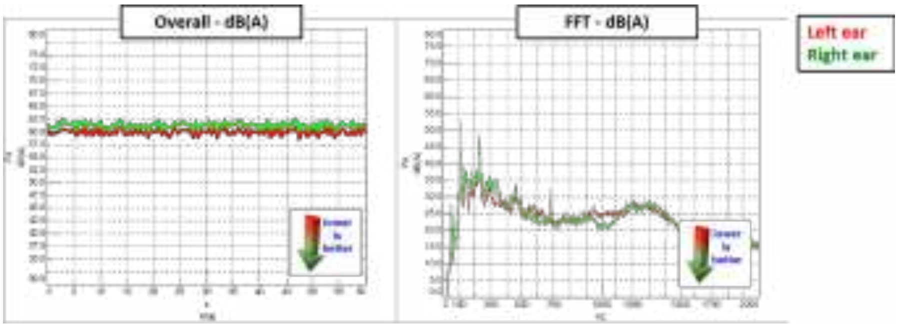


Figure 19: Operative climatic chamber and vehicle doors closed – engine off

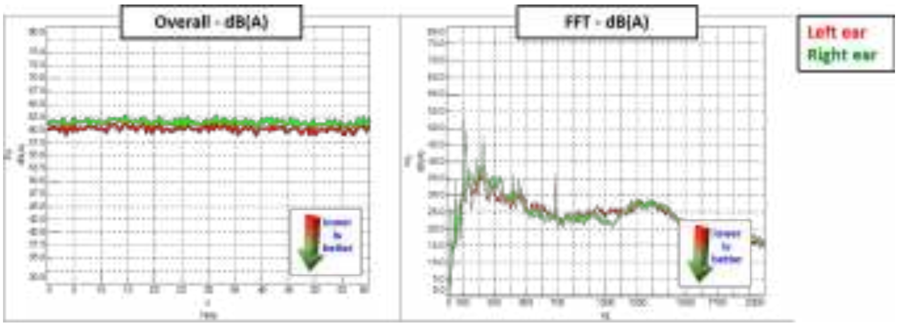


Figure 20: Operative climatic chamber and vehicle doors closed – engine on and HVAC at level 1

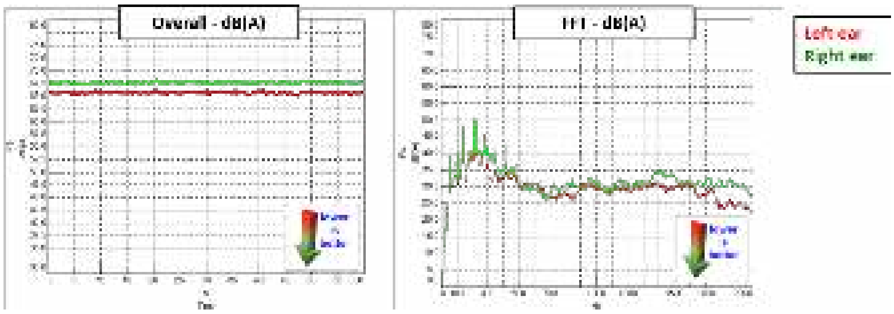


Figure 21: Operative climatic chamber and vehicle doors closed – engine on and HVAC at level 4

The overall noise level when the climatic chamber was not operated always kept higher than 30 dB(A), however when the doors were closed the noise level inside the Fiat 500 was as lower as about 20 dB(A). However, when the climatic chamber was operated the noise level inside the car raised as high as more than 60 dB (A), irrespectively whether the engine was on or off.

On the opposite when the HVAC ventilation was set at the highest regime, the overall noise level reached a value higher than 65 dB (A).

Subsequently, the sound heard by the subjects through the earphones (EV car noise at constant speed) was measured in several different configurations:

- still climatic chamber and vehicle doors closed – engine off
- still climatic chamber and vehicle doors closed – engine on and HVAC at level 1
- still climatic chamber and vehicle doors closed – engine on and HVAC at level 4
- operative climatic chamber and vehicle doors closed – engine on and HVAC at level 1
- operative climatic chamber and vehicle doors closed – engine on and HVAC at level 4

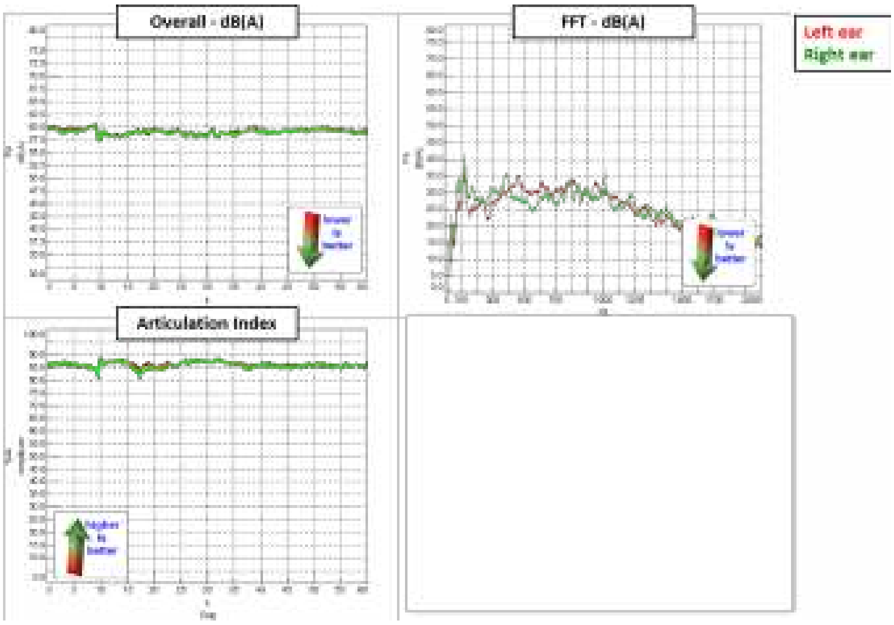


Figure 22: Still climatic chamber and vehicle doors closed – engine off

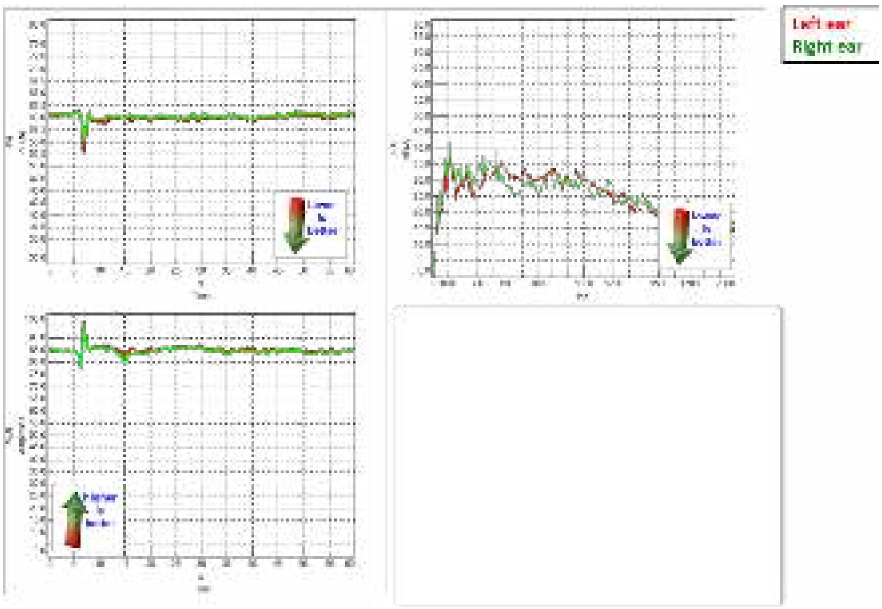


Figure 23: Still climatic chamber and vehicle doors closed – engine on and HVAC at level 1

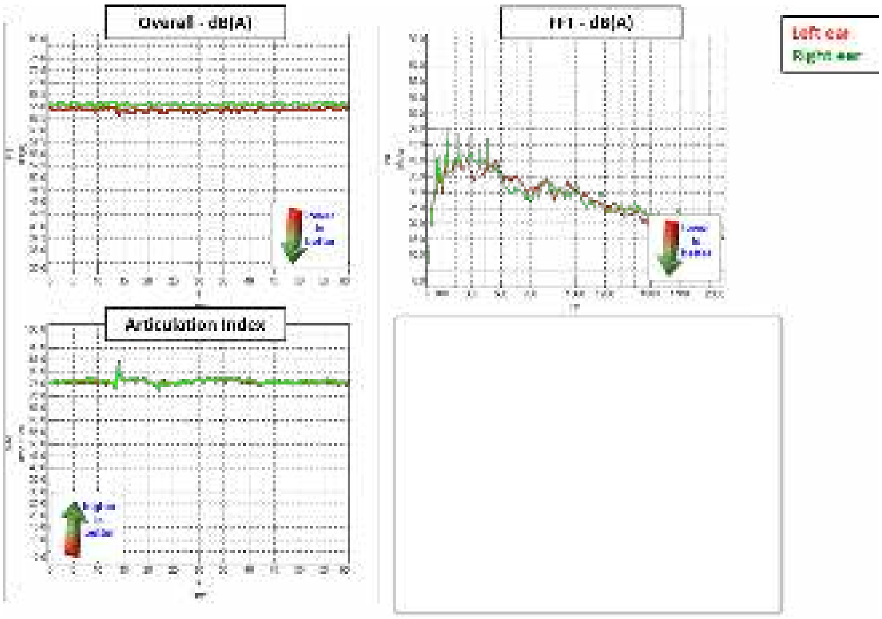


Figure 24: Still climatic chamber and vehicle doors closed – engine on and HVAC at level 4

When the climatic chamber was still, what happen most of time when the ambient temperature was within 1 °C from the target temperature (equal to 22°C), the sound level (around 60 dB(A)) allowed an articulation index of more or less 85% by the fist level of ventilation, very close to the values attained when the engine was off.

However, the articulation index lowered to 76% when the engine was fired, and the ventilation was set the highest level.

When the climatic chamber was operated, the articulation index was only slightly worsened by less than 3%.

The questionnaires were translated into the Italian language, the latter being the mother tongue of all the participants; the translation was verified and approved by an English native speaker.

The sun radiation was emulated by means of a laboratory solar lamp emitting radiation reproducing the solar spectral emission (Picture 7).

Picture 7: GOYA 2,5/4 kW Dual Power Daylight Broad-Light

Such lamps can be operated at both 2.5 kW and 4.0 kW power emitting more than 3.000 lux at a distance of around 6 meters at a maximum ambient temperature of 45 °C and are generally used to appraise the efficiency of photovoltaic panels (Picture 8).

Picture 8: Setup for the test of photovoltaic panels

The light illuminance inside the car cabin placed in the climatic chamber was measured with both solar lamp on and off, by means of the Illuminance Spectrophotometer CL 500A produced by Konica Minolta, complying with the requirements of DIN standard 5032 Part 7, Class B in the wavelength range from 360 to 780 nm.

The illuminance at the at participant eyes level resulted to be 5.49 Lux and 4.63 Lux for either eye in mesopic vision, 9.45 and 7.90 respectively in scotopic vision, with the solar lamp on.
The light spectrum measured by the instrument through the glass window is shown in Figure 25.

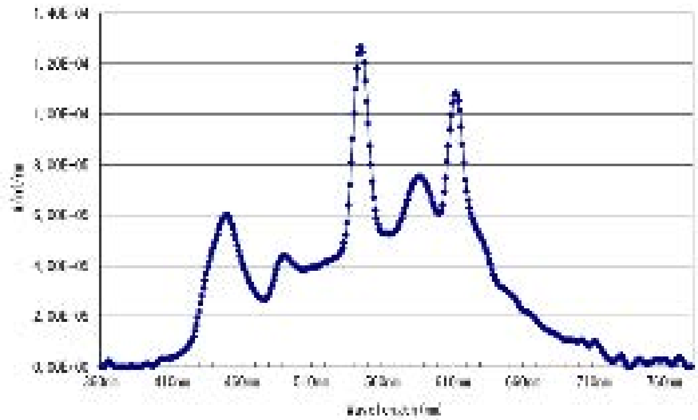


Figure 25: Light spectrum

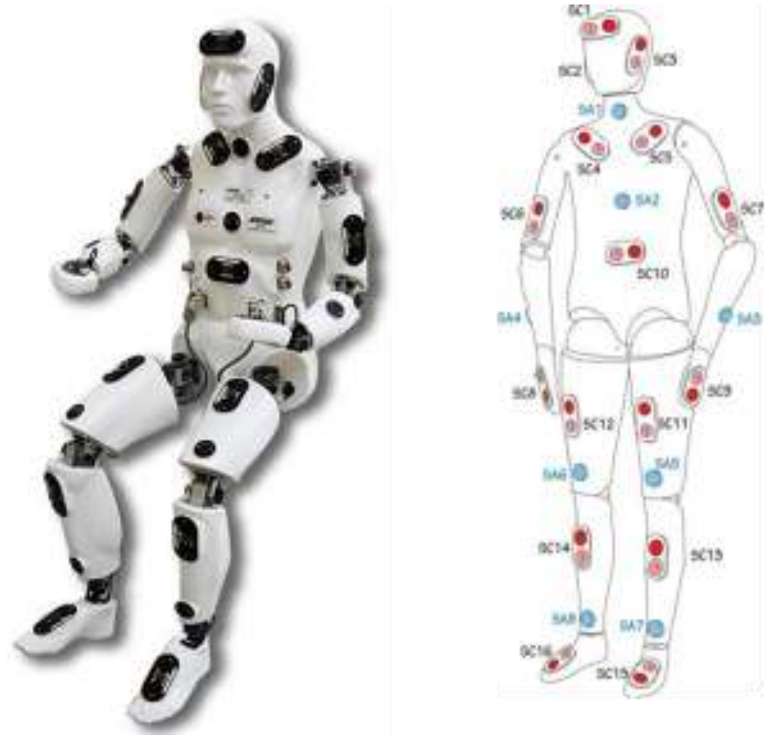
As far as the ambient scent is concerned, “Neutral” scent from “Envii Bed Fresh” not being available, an equivalent scent was sprayed at each testing session, namely “Neutrodor Tessuti” from “Arbre Magique”.

Thermal dissymmetry objective test

Besides the subjective testing campaign, objective measures were taken by means of a proprietary thermal manikin (Picture 9) which on the basis of the Fanger’s model, combining four physical variables (air temperature, air velocity, mean radiant temperature and relative humidity), and two personal variables (clothing insulation and activity level) allows to estimate the Predicted Mean Vote.

Picture 9: Proprietary Thermal Comfort Manikin P. A. C. O.

The relevant four physical variables are measured by means of the P.A.C.O. Manikin (see Figure 26), carrying 16 comfort sensors (see Figure 27) and 8 temperature and humidity sensors.



SC1	Head
SC2	Righ cheeck
SC3	Left ceeick
SC4	Righ shoulder
SC5	Left shoulder
SC6	Right arm
SC7	Left arm
SC8	Right hand
SC9	Left hand
SC10	Thorax
SC11	Left thigh
SC12	Right thigh
SC13	Left shin
SC14	Right shin
SC15	Left foot
SC16	Right foot
SA1	Neck
SA2	Thorax
SA3	Left arm
SA4	Right arm
SA5	Left leg
SA6	Right Leg
SA7	Left foot
SA8	Right foot

Figure 26: P.A.C.O Manikin

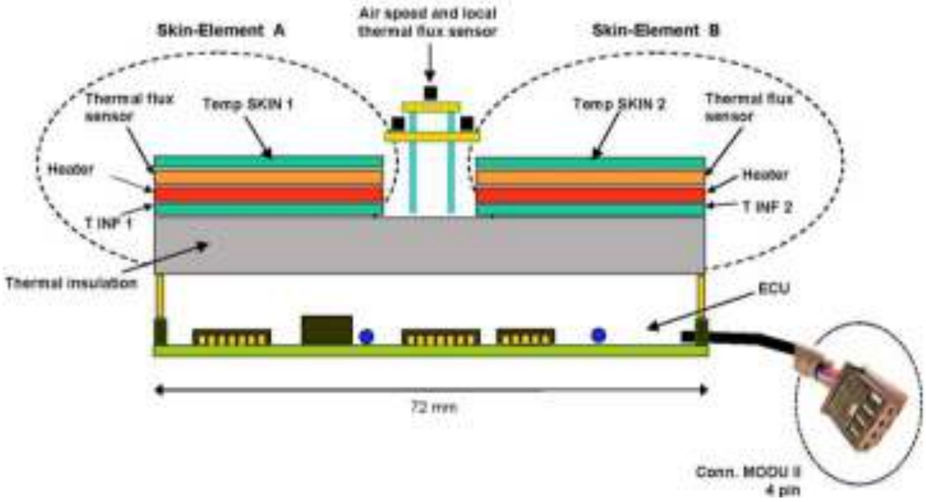


Figure 27: Comfort sensor

From the measures collected by the comfort sensors and environmental sensors the equivalent temperatures can be calculated for different body areas, by means of calibration parameters previously estimated through experimental testing in an environment with homogeneous air and boundary surface temperatures, in still air.

Such parameters are embedded in the P.A.C.O. Manikin operating SW.

Clothing insulation is measured in units of ‘CLO’, estimated using tables that have been developed from clothing insulation studies, conducted in laboratory experiments devoted to this purpose; average CLO values typically range from 0.35 to 0.60 CLO in summer and from 0.80 to 1.20 CLO in winter.

Activity level is measured in terms of metabolic rate, or ‘MET’ (1 MET = 58.2 W/m2) which are based on tables of MET rates for specific activities and occupations, developed from laboratory studies. Usually 1.20 met value for sedentary activity level is assumed; however the MET rate for a given activity is influenced by a person’s body mass, body type, fitness and blood flow so that MET can range from 1.0 to 1.9 between people and over time.

The CLO parameter was set to 0.76 and MET parameter to 1.2 consistently with the subjective experimental protocol.

Once equivalent temperatures are known, by selected CLO and MET values, the Predicted Mean Vote can be calculated, consistently with Fanger's comfort model, by a weighted mean among different body areas.

Objective measurements were carried out at three different climatic chamber temperatures: 17, 22, 27°C with PACO manikin in front passenger seat; the tests were performed with Air Conditioning ON.

The test procedure was as follows:

- Test phases at 17°C:

dashboard outlets in neutral position
set T object = 17°C

0. minimum HVAC blower velocity; air distribution in dashboard outlets; duration 5 minutes
1. lateral sun simulator switching on; duration 10 minutes
2. move the lamp away; duration 5 minutes
3. close the right central outlet, set the blower at medium and maximum velocity (3 and 4 m/s at the lateral outlet surface); duration 5 minutes each
4. test end

- Test phases at 22°C:

dashboard outlets in neutral position
set T object = 22°C

0. minimum HVAC blower velocity; air distribution in dashboard outlets; duration 5 minutes
1. lateral sun simulator switching on; duration 10 minutes
2. move the lamp away; duration 5 minutes
3. close the right central outlet, set the blower at medium and maximum velocity (3 and 4 m/s at the lateral outlet surface); duration 5 minutes each
4. test end

- Test phases at 27°C:

dashboard outlets in neutral position
set T object = 27°C

0. minimum HVAC blower velocity; air distribution in dashboard outlets; duration 5 minutes
1. lateral sun simulator switching on; duration 10 minutes
2. move the lamp away; duration 5 minutes
3. close the right central outlet, set the blower at medium and maximum velocity (3 and 4 m/s at the lateral outlet surface); duration 5 minutes each
4. test end

The total duration for one test was 30 minutes.

6.2.3Relevant findings

During the subjective test, participants evaluated their thermal comfort related to the following body parts:

- Overall
- Front trunk
- Rear Trunk
- Feet
- Left upper arm
- Left lower arm
- Right upper arm
- Right lower arm

The evaluated configurations are displayed in Table 10. The evaluation scale is presented in

Table 11.

Table 10: Configuration evaluated in CRF study

	Test case	Vents	Open / Close	Environmental factors				
				T AIR	Irradiation	V AIRFLOW on vents	Vents position	
	ID			[°C]	[W/mq]	[m/s]		
T0 - V1 - Bneut - first	0	Central Lateral	Open Open	22	0	1	Neutral	evaluation **at ingress** in car
T0 - V1 - Bfree	1	Central Lateral	Open Open	22	0	1	Personal moving	evaluation **5 min after** setting
T0 - V1 - Bneut + Sun	2	Central Lateral	Open Open	22	500	1	Neutral	evaluation **10 min after** setting
T0 - V1 - Bfree + Sun	3	Central Lateral	Open Open	22	500	1	Personal moving	evaluation **5 min after** setting
T0 - V1 - Bneut - second	4	Central Lateral	Open Open	22	0	1	Neutral	evaluation **5 min after** setting
T0 - V3 - Bneut - noBcentral	5	Central Lateral	Close Open	22	0	3	Neutral	evaluation **5 min after** setting
T0 - V4 - Bneut - noBcentral	6	Central Lateral	Close Open	22	0	4	Neutral	evaluation **5 min after** setting
ALL FREE	7	Central Lateral	Open Open	Personal setting	0	Personal setting	Personal moving	evaluation **5 min after** setting

Table 11: Thermal sensation scale used in CRF study

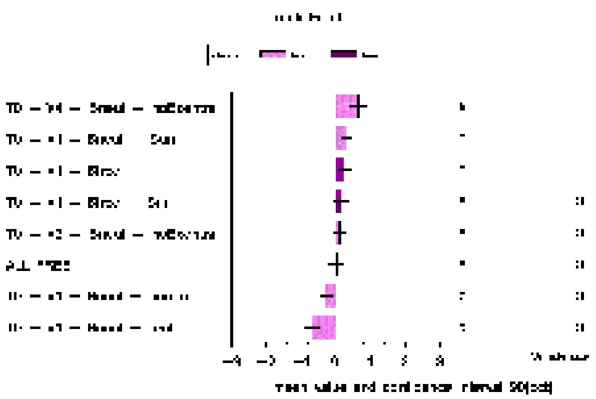
-3	-2	-1	0	+1	+2	+3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

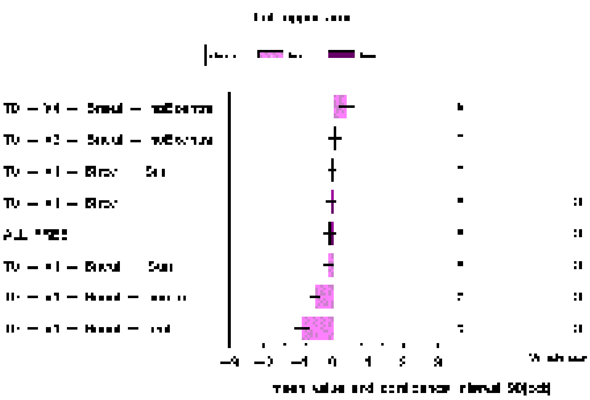
Only 28 participants among the 31 involved have been considered in the analysis (3 of them have been excluded because correlations of their evaluations with the average of others were negative).

For each considered aspect, the following indicators have been considered:

- Mean value (and related confidence interval at level of 90%) of each configuration in order to identify the ranking of a configuration compared to the others;
- Groups of configurations with mean values significantly different (one letter represents one group: configurations into the same group, that is with the same letter, are not significantly different among themselves at chosen level of confidence using the Duncan test).

Aspects in which it is possible to observe some differences among configurations are front trunk and different parts of arms (the areas which created thermal asymmetries are aimed at). Graphs related to these aspects are reported below.





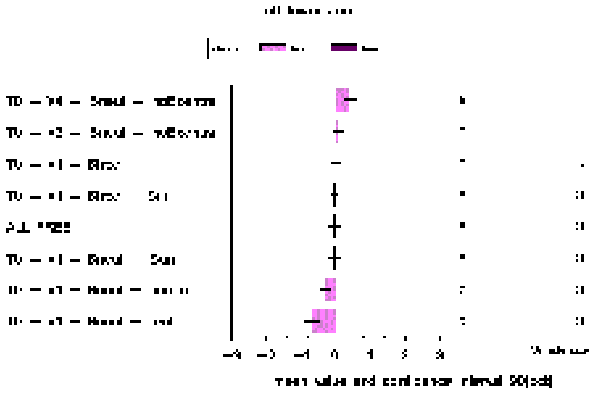


Figure 28: Thermal sensations for "trunk front", and "left upper and lower arm" for different configurations

For Front trunk, Left upper arm and Left lower arm: in configuration "T0 – V4 – Bneut – noBcentral" participants declare they feel Slighty Warm, whereas in configurations "T0 – V1 – Bneut – second" and "T0 – V1 – Bneut – first" they feel Slightly Cool (but mean evaluation of "T0 – V1 – Bneut – first" is lower than "T0 – V1 – Bneut – second" one).

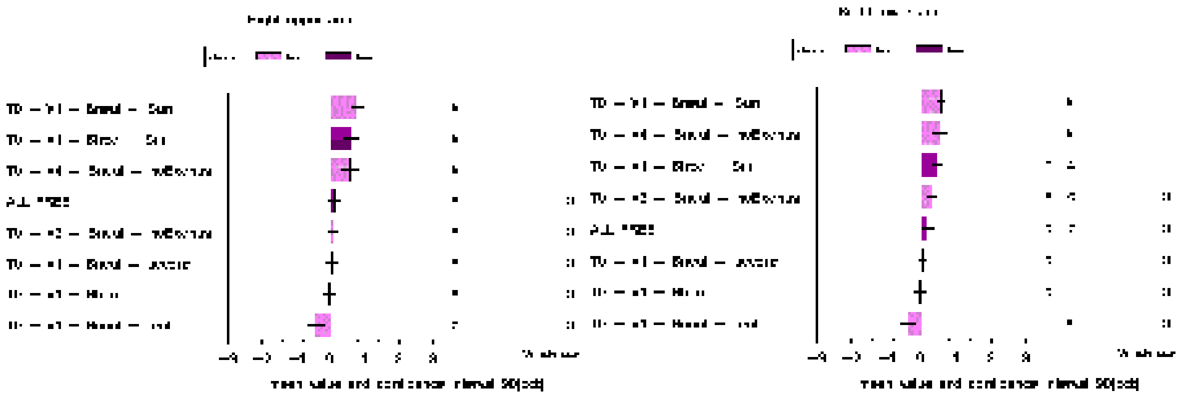


Figure 29: Thermal sensations for "right upper and lower arm" for different configurations

For Right upper arm and Right lower arm: in configurations "T0 – V4 – Bneut – noBcentral", "T0 – V1 – Bneut + Sun" and "T0 – V1 – Bfree + Sun" participants declare they feel Slighty Warm, whereas in configuration "T0 – V1 –Bneut – first" they feel Slightly Cool.

For other body parts, participants don't feel significant differences in tested configurations.

To compare the experimental data acquired by the thermal comfort manikin PACO (positioned on the car in the front right passenger seat) with the results of the analysis regarding the subjective evaluations just described, the attention has been focused on the tests carried out at the air temperature of 22 ° C in climatic chamber; the main phases are summarized by highlighting the correspondences with the respective wordings used to describe the phases of subjective tests carried out in the same conditions and timing of acquisition:

- Phase 1 (PACO Test) = T0-V1-Bneut-first (SUBJECTIVE Test): T.object = 22°C; A/C on; min HVAC blower; dashboard outlets open
- Phase 2 (PACO Test) = T0-V1-Bneut+Sun (SUBJECTIVE Test): T.object = 22°C; A/C on; min HVAC blower; dashboard outlets open; lateral solar irradiation
- Phase 3 (PACO Test) = T0-V1-Bneut-second (SUBJECTIVE Test): T.object = 22°C; A/C on; min HVAC blower; dashboard outlets open
- Phase 4 (PACO Test) = T0-V3-Bneut-noBcentral (SUBJECTIVE Test): T.object = 22°C; A/C on; medium HVAC blower; dashboard outlets open; central right outlet closed

- Phase 5 (PACO Test) = T0-V4-Bneut-noBcentral (SUBJECTIVE Test) : T.object = 22°C; A/C on; maximum HVAC blower; dashboard outlets open; central right outlet closed

The graph in Figure 30 shows the trends of the Equivalent Temperature detected by the respective sensors mounted in different zones of the PACO manikin body.

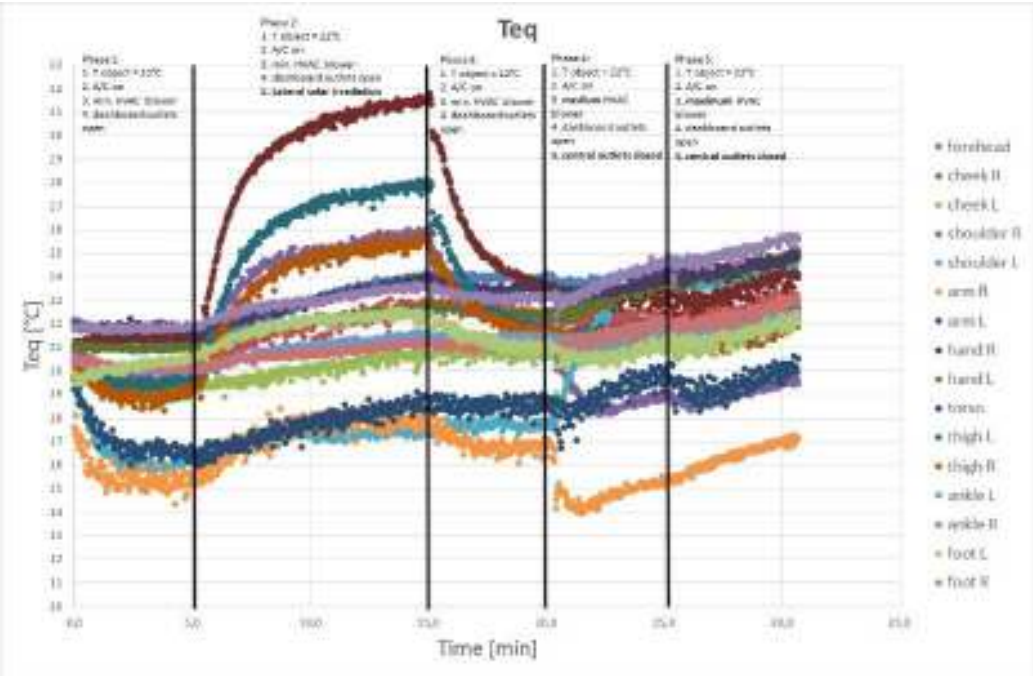


Figure 30: Equivalent Temperatures over time

The curves show that in the first three initial test phases (phase 1,2,3) the Equivalent Temperatures detected by the arms right and left and shoulder left sensors are about 4 - 5 ° C lower than the values detected by the other sensors.

Furthermore, in the last two test phases (phase 4 and 5) the Equivalent Temperatures of the shoulder left zone increases while the corresponding one of the shoulder right zone decreases (as it happens for the arm right zone), due to the closure of the right central outlet on the dashboard, with a consequent increase of the average speed values of the air measured by the anemometers mounted on the arm right and shoulder right sensors (Figure 31).

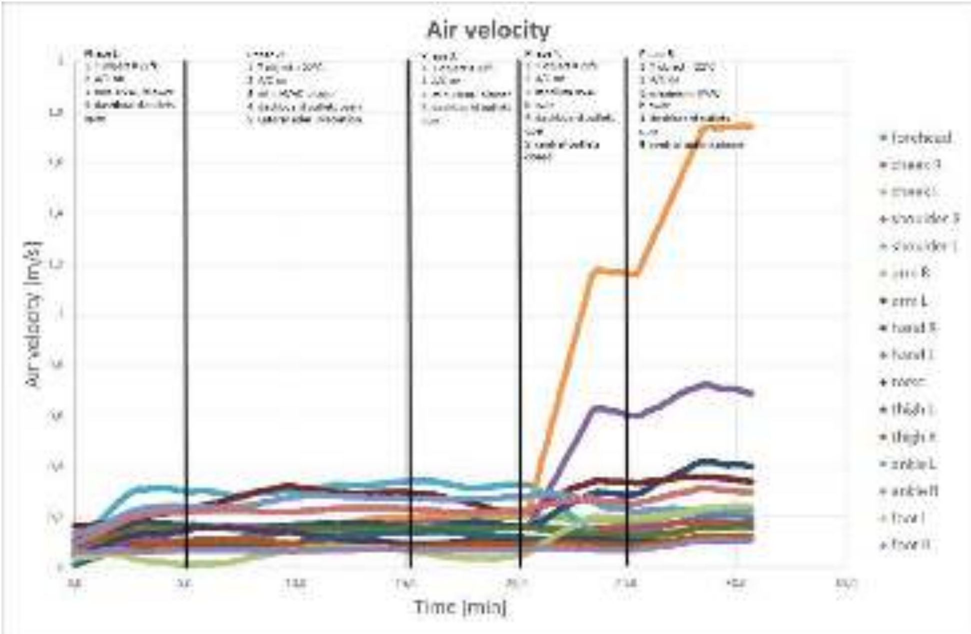


Figure 31: Air velocity over time

These trends are consistent with the subjective assessments and largely explain why during the subjective tests the jurors perceive the front trunk areas, left upper arm and left lower arm, such as:

- slight warm -> during the test phase T0 V4 Bneut no B central
- slight cool -> during test phases T0 V1 Bneut first and second.

During the phase 2, characterized by the application of an external light source, it can be seen how the irradiation mainly affects the following PACO sensors, thus determining an increase in the temperatures detected in those areas of the body of the thermal manikin: hand right (mainly), thigh left and right, shoulder right.

In this case – also - the trends are consistent with the subjective data and explain why during the subjective tests the jurors perceived the right upper and lower arms as slight warm in phase T0 V1 Bneut Sun

The graph (Figure 32) relating the only air temperatures measured in different areas of the manikin confirms that the effect of irradiation causes an increase of the values measured by the sensors corresponding to the thigh left and arm right zones.

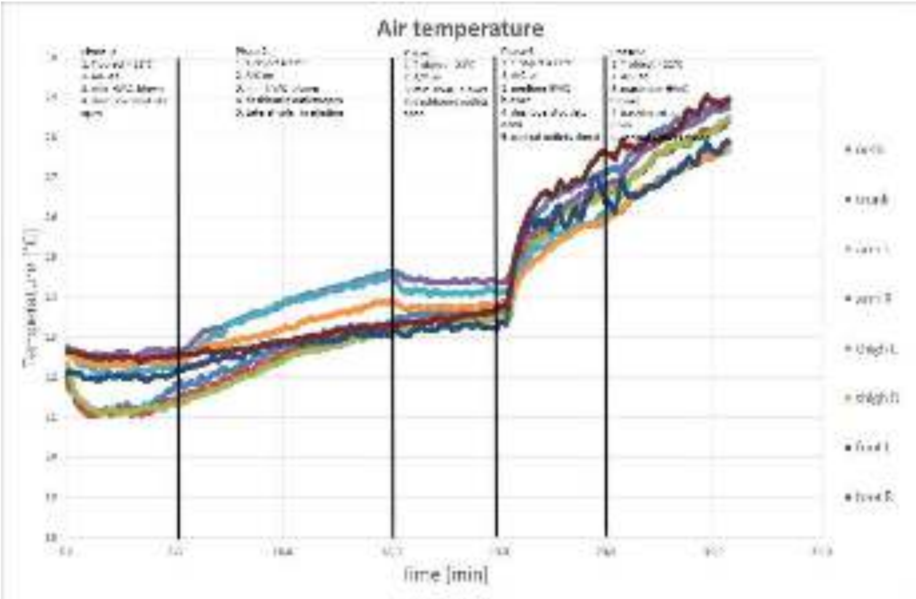


Figure 32: Air temperatures over time

As for the graph of the Equivalent Temperatures also the corresponding one of the air temperatures shows how the values are increasing during the test phases and in particular for the last two test phases: this is particularly consistent with the "slighty warm" subjective assessment for the zones right upper and lower arm during the final phase T0 V4 Bneut no B central.

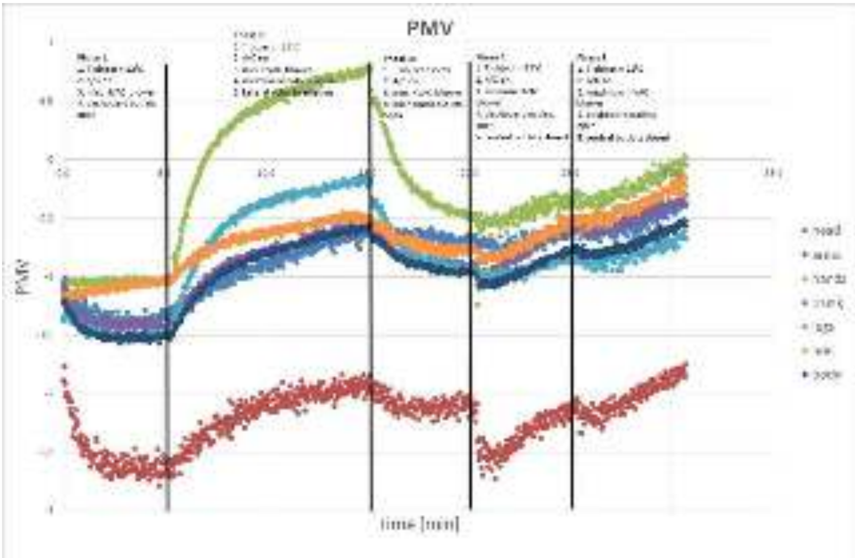


Figure 33: PMV index over time

The analysis of the PMV index curves (Figure 33), calculated for the main areas of the manikin, confirms the subjective data and highlights how:

- The lowest values of the PMV index, tending to cold, refer to the data detected in the arms areas of the PACO manikin in all the test phases
- The introduction of an external radiation source leads to an increase in temperatures and in the PMV index for the hand area
- The PMV index rises in the last two phases due to the increase of the air temperature due to the closure of the central right outlet on the dashboard.

6.2.4 Discussion

Both subjective and objective tests were based on two main external disturbances with the goal to generate thermal dissymmetries which have been detected both by participants and by PACO thermal manikin.

The application of the external light source has been perceived by participants with a warm-up of right arms and by some manikin sensors, in particular right hand and right shoulder. The closure of central outlet has generated a heating of the car cabin air as a result of a lower quantity of air entering the car cabin. This event has been perceived by participants with a warm-up of both arms and front trunk; moreover PACO has shown that air temperatures increase during this phase at all its sensors, whereas equivalent temperature increases for left shoulder as consequence of closure of central outlet.

6.3 ika study – radiation wavelength and thermal comfort

Following the grant agreement, the Institute for Automotive Engineering Aachen (ika) of RWTH Aachen University, Germany, planned to conduct a study to validate and improve existing thermal comfort models.

Widely used comfort models, i.e. as proposed by Fanger (1970), estimate the thermal sensation in a step and comfort perception in a second step by weighting the environmental conditions of air temperature, thermal radiation, air speed, and air humidity. However, these models neglect the spectrum of radiation. A user study at ika examined the hypothetical relevance of this parameter for the sub-construct of comfort "thermal comfort" in order to pave the way for its integration into current elaborated models. Due to technical specificities the two spectra IR-A (λ = 0.78 µm to 1.4 µm) and IR-C ($\lambda \geq$ 3 µm) were examined in this user study. The results are discussed to serve as an extension of current thermal models and may therefore lead to a deeper understanding regarding thermal sensation, comfort perception as well as their influencing factors.

6.3.1Introduction

The set-up of ika's study followed the general guidelines of section 5 in order to compare the differences of IR-A and IR-C on thermal sensation, the study was conducted in a thermo-acoustic chamber (TAC) on the premises of and by an interdisciplinary research team composed of psychologists and engineers of ika. Subsequent to an initial survey phase, the participants were confronted with two different air temperatures and two different radiation spectra. All participants were positioned in two different standardised distances relative to the radiation sources, respectively (Figure 34). This led to two levels of irradiance as independent variables. The dependent variables were thermal sensation, thermal comfort, and physiological reactions operationalised via subjective questionnaires and the assessment of objective physiological data regarding skin temperature, heart rate, skin conductance, and blood volume pulse.

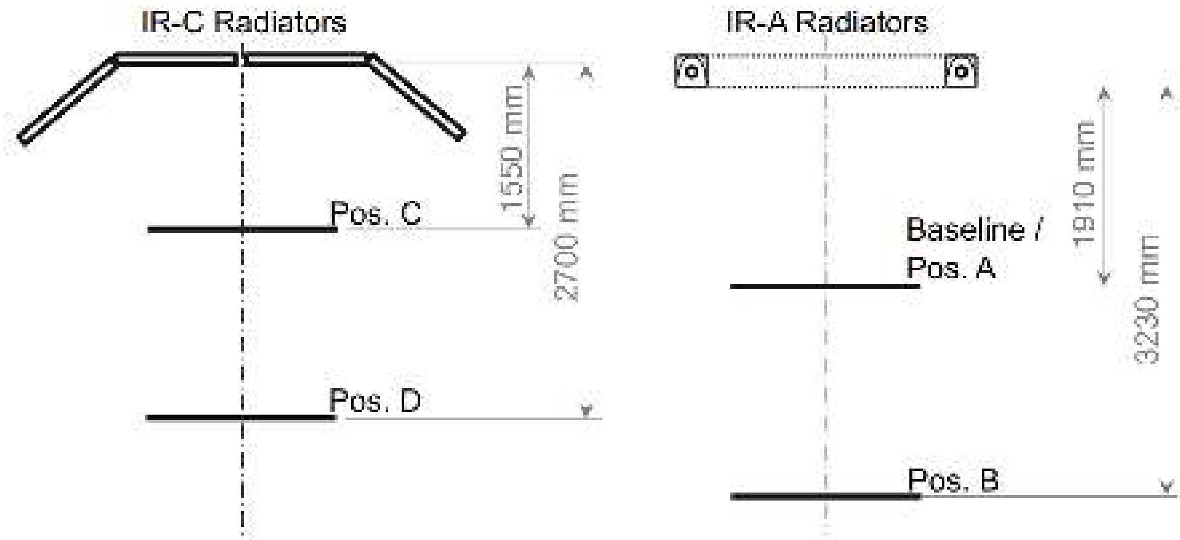
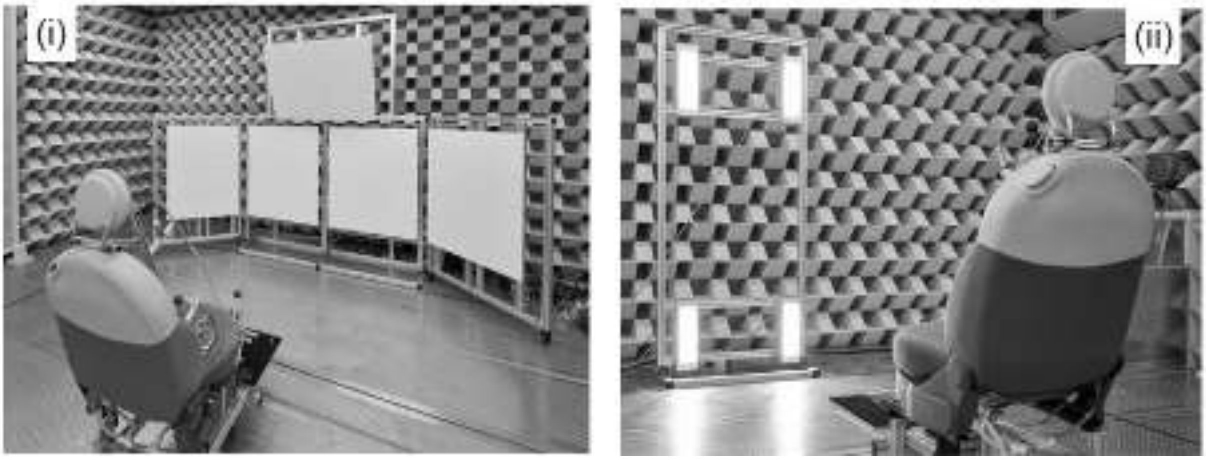


Figure 34: Participants were positioned in four different positions (A-D) in front of the two types of radiators. Note: The radiators on the right hand side emitted IR-A radiation. The radiators on the left hand side emitted IR-C radiation. Positions A and C represented an irradiance of 200 W/m², whereas positions B and D represented an irradiance of 100 W/m². Position A was also used with a deactivated IR-A radiator as a baseline (0 W/m²).

Apparatus, Task and Stimuli

In order to examine the influence of different types of radiation on thermal sensation, an experimental setup was build up in the TAC on the premises of the Institute for Automotive Engineering (see Picture 10). The chamber provides a controlled environment regarding acoustics, air temperature, air speed, and humidity. Two different types of radiative heaters were installed to provide two radiation spectra mainly composed of IR-A and IR-C, respectively. On one side of the chamber, a radiation source with a peak wavelength at 1.2 µm was installed (see Picture 10 ii). Its radiation was mostly composed of IR-A, with an additional share of visible light. On the other side a long-wavelength radiation source, with almost exclusively IR-C, peak wavelength at ~8 µm, was installed (see Picture 10 i).



Picture 10: The experimental setup, featuring (i) IR-C radiators and (ii) IR-A radiators, and a relocatable chair.

Both radiative sources had a high level of emissivity (ε > 0.9) and are therefore comparable to the theoretical concept of an idealised black-body radiator (ε = 1). As a close approximation to reality, Figure 35 depicts the theoretical radiation spectra of according blackbody radiators. To justify the selected types of radiation it is worthwhile to mention that these are also prevalent in the real world. For instance, sunlight being filtered by the atmosphere is mainly composed of visible light and IR-A radiation, while heated surfaces ordinarily range in the IR-C area.

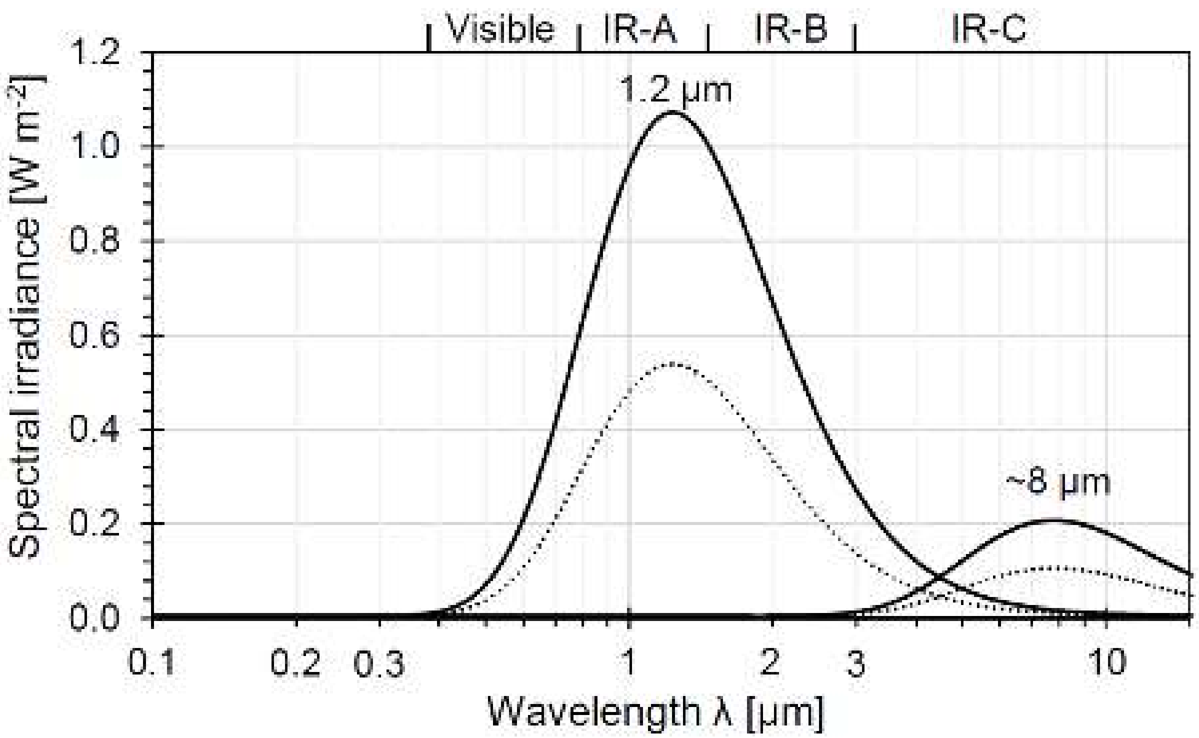


Figure 35: Theoretical irradiance from two different idealised black-body radiators onto a reference plane. Note: The first irradiance with a peak wavelength at 1.2 µm prominently consists of IR-A, with additional components in the IR-B and visible domain. The second irradiance with a peak around 8 µm is mostly composed of IR-C radiation. The two solid lines represent a total irradiance of 200 W/m², while the dotted lines correspond to 100 W/m².

To guarantee for comparability between the conditions, the range of irradiance (radiant flux received by a surface) had to be standardised to a similar level. Furthermore, a homogenous distribution of irradiance received by the participants had to be assured. The prescribed irradiance values refer to a defined vertical reference plane with a height of 1400 mm and a width of 600 mm. These values were considered to be high enough for being perceived and low enough to comply with safety standards. The distance between radiation sources and the participants' centre position could be altered in a standardised manner, so that both positions near the radiation sources (positions A and C) had an irradiance level of 200 W/m² and the positions with a long distance (positions B and D) had an irradiance level of 100 W/m² (see Figure 34). Irradiance was almost exclusively applied from the front side. Congruent with previous section, the air temperature was altered additionally to better understand the relationship between the independent variables. Therefore, two different air temperatures, 16 °C and 22 °C, were examined. The identification of these two temperatures was based on Fanger (1970) and Nilsson et al (1997). Based on these models a neutral thermal sensation was expected by an air temperature of 22 °C. The second air temperature of 16 °C was expected to be perceived as cold, however still not overshadowing effects by additional radiation sources.

Safety measures

To avoid both, any damage to the eye by the IR-A radiator and a visual estimation of the power of the radiators, participants were blindfolded as soon as they entered the TAC. A sight protection was built on protective goggles with radiation reflecting material, which did not let any light pass. The safety goggles were only removed behind sight protection, where participants could not see the radiators. Participants were seated on a relocatable car seat of a Fiat 500, and moved through the TAC to the 4 different experimental positions A-D (see Figure 34) in front of the two types of radiators. The radiators on the right hand side emitted IR-A radiation. The radiators on the left hand side emitted IR-C radiation. Positions A and C represented an irradiance of 200 W/m², whereas positions B and D represented an irradiance of 100 W/m². Position A was also used with a deactivated IR-A radiator as a baseline with 0 W/m² irradiance.

Dependent Variables

Two item sets were used to assess the thermal sensation and comfort perception in each test case. Following ISO 14505-3, item set S1 was short and included only two items. One item aimed for thermal sensation on a 7-point scale from cold (1) over cool, slightly cool, neutral to slightly warm, warm and hot (7). The other item targeted the perceived thermal comfort on a 9-point scale from 1 (not comfortable) to 10 (very comfortable). This item set S1 could assess a brief thermal sensation and comfort perception very quickly.

Item set S2 included an extensive assessment of ISO 14505-3 with various items regarding thermal sensation, wind, and humidity perception at different body parts (overall, head, arms, trunk, and feet) and a comparison to earlier experienced conditions. This thermal sensation scale compared the overall sensation with the sensations at the head, front, and rear trunk, arms, hands, and feet with the same 7-point scale from cold to hot, as is it used in the item set S1. The perceived air humidity was assessed on a 4-point scale from not sticky (1) to slightly sticky, sticky, and very sticky (4). Two dichotomous items (yes or no) assessed, if any sort of heat or wind was perceived and if so, an open question was asked on how participants would describe this perception. The multisensory comfort was assessed similar to the second item of item set S1. Here, the thermal environment, seating, olfactory environment and overall situation was assessed. This collection of questionnaires was based on ISO 14505-3 and is therefore comparable with the other studies presented in this deliverable. The time to discomfort was assessed based on Thom (1959). Here, two open items assessed for how many minutes the participants would endure the current situation and for how many minutes they would consider the situation as acceptable. The NASA TLX assessed the workload, as depicted in section 5.5.3 (NASA, 1986). A final open question asked if participants wanted to add anything in item set S2.

As all participants were blindfolded, all questionnaires of Item Set S1 and S2 were interview questions, read out loud by the instructor. The secondary task was also auditory and presented via headphones, so that the participants were not disturbed by any noise the radiant heaters might produce.

Secondary task

The secondary task consisted of spoken numbers from one to five every five seconds. Participants were instructed to add the last two numbers heard and report the result verbally. The numbers were presented with 80 dB on top of a background noise with 53 dB. The secondary task's workload was assessed via the NASA-TLX.

Physiological Data

Physiologic data like skin conductance, heart rate, and skin temperature was assessed with BioGraph Infiniti Software. As the scope of this deliverable is on subjective perception, physiological data will not be included in the results section and instead be published in a scientific journal. The subjective questionnaires of item sets S1 and S2 will be the main focus for the analysis of section 6.4.3.

6.3.2Test cases

For comparing the effects of IR-A and IR-C, participants experienced three independent variables (radiation, irradiance, air temperature) which are displayed in Table 12.

Table 12: ika experimental design with test case reference numbers

			Test cases				
Radiation	-	None	IR-A		IR-C		None
Level of Ir-radiance	-	0 W/m²	200 W/m²	100 W/m²	200 W/m²	100 W/m²	0 W/m²
Description	Participant room	Baseline TAC	Experimental conditions in TAC randomised for each block				Baseline TAC
Blocked air in TAC 16 °C	1	2	3	4	5	6	7
Blocked air in TAC 22 °C	8	9	10	11	12	13	14

Within each factor level of air temperature in TAC (16 °C and 22 °C), participants experienced the two levels of the factor radiation (IR-A and IR-C). Each of these infrared radiation spectra had two levels of irradiance (200 W/m² and 100 W/m²). Due to technical limitations of the Thermo-Acoustic Chamber (TAC), the air temperature was presented blockwise at 16 °C or 22 °C. Participants had to attend on two separate days. This resulted in a 2✕2✕2 within-subject design including eight experimental test cases per participant (test cases 3-6 for 16 °C and test cases 10-13 for 22 °C). Furthermore, there were three baselines for each block of the factor air in TAC, i.e. six baseline measurements. Test cases 1 and 8 were conducted in a participant room before entering the TAC. The other four baselines (test cases 2 and 7 for 16 °C and test cases 9 and 14 for 22 °C) were conducted inside the TAC without additional radiation. Summing up, the resulting fourteen test cases of tab. 3 were eight experimental conditions (test cases 3-6 and 10-13) and six baseline measurements (test cases 1-2, 7-9 and 14). Half of the participants experienced the cold (16 °C) and half of the participants the warm block of the factor air in TAC (22 °C) as their first block. The scheduling of the two blocks was kept comparable (e.g. two Mondays, one week apart at 8 o'clock each). Within each block, the experimental conditions were balanced.

Procedure

The study was conducted during May and June 2019. Upon arrival, participants were instructed to read and sign the required formal documents. Subsequently, the physiological measurement equipment (ProComp Infinity) was attached to the participants.

Afterwards, they were instructed to relax for approximately five minutes in the participant room to assess the first baseline. Participants then entered the TAC. Subsequent to this, further questions on demographics, thermal sensitivity, acoustic preferences, skin characteristics and thermal history were answered. The study was conducted according to the test plan (section 5.6). For all experimental conditions and the last baseline, participants completed three trials of the secondary task. Each trial lasted about one minute, followed by item set S1 (see section 5.6). At the end of each test case with the secondary task, participants completed item set S2. Subsequent to this experimental phase, participants were escorted to the participant room and received a debriefing. Each participant was tested for two hours per block, resulting in four hours in total.

Participants

Using the G*Power tool (Faul et al., 2007) for a repeated measurements analysis of variance (ANOVA) the following assumptions were stated a priori. Assuming a small effect size of f = 0.2, an alpha error of α= 0.05, a power of 1 – β = 0.9, a correlation among repeated measurements of r = 0.5 and a non-sphericity correction error of E = 0.9, a within subject design with ten measurements would need a sample size of N = 28 participants for an F = 1.98. Therefore, N = 30 participants were invited and N = 29 data sets were collected. Out of N = 29 participants, n = 15 were female (52 %). The age groups were almost balanced (n20-29 years = 8 participants; n30-39 = 4; n40-49 = 5; n50-59 = 6; n60-69 = 6) while participants' ages ranged from 20 to 69 years. N = 28 from N = 29 participants followed the instructed dress code of standardised clothing including a t-shirt, long trousers and regular shoes resulting in a clothing level of 0.55 clo. In contrast to section 5.4.2, the clothing level did not include a long sleeve shirt, because the effects of infrared radiation on the skin can be measured more precisely, when the skin is exposed to the infrared radiation.

6.3.3 Relevant results

This section will focus on selected results regarding the influences of IR-A and IR-C on thermal sensation. All further results will be published in a scientific journal.

The analysis in this section is based on the thermal sensation score via the first item of item set S1 after five minutes into the experimental condition, which represents the third trial in any condition. This item is based on ISO 14505-3 and rated via a 7-point scale from cold over cool, slightly cool, neutral to slightly warm, warm and hot. Due to its ordinal scale level, a Friedman-test and Wilcoxon post-hoc comparisons were conducted using IBM SPSS Statistics Version 23. The results are displayed in Figure 36.

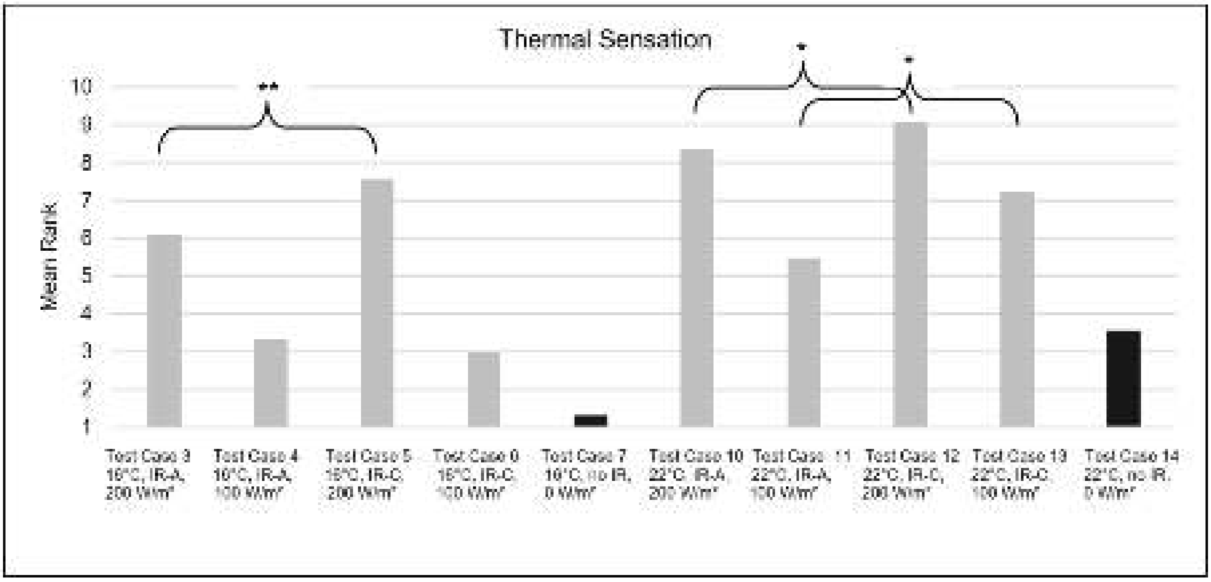


*Figure 36: Results of the thermal sensation for all experimental conditions (grey bars) and the last baseline per temperature block (black bars), in which subjective assessments were made (test cases 3-7 and 10-14). The y-axis shows the mean rank ranging from 1 to 10. The significances of the posthoc non-parametric Wilcoxon signed-rank tests are marked in the figure above, * p < .05, ** p < .01.*

Using IBM SPSS Statistics Version 23 a non-parametric Friedman test was run to analyse the differences in thermal sensation for all test cases (see Table 4). The Friedman test revealed significant differences for the test cases compared, $X^2 = 205.30$, $p < .001$. Results of post-hoc Wilcoxon signed-rank tests, to compare test cases 3 and 5; 4 and 6; 10, and 12; 11 and 13, are reported in Figure 36. The differences between test cases 3 and 5; 10 and 12; and 11 and 13 are significant. The comparison between test cases 4 and 6 revealed no statistical difference.

Discussion of relevant results

One main result of this study is that thermal radiation is able to alter human subjective temperature rating. This finding supports that the energy management of electric vehicles can be improved by using only radiant heat giving the occupant the sensation of a higher temperature of the environment.

This effect is observed for both of the used spectra, IR-A and IR-C, however the effect was more prominent for IR-C in three out of four cases, indicating distinguishable effects for the two spectra on thermal sensation. Only in 16° C air temperature with low irradiance level (100 W/m²) results showed no significance. These results imply that a difference between IR-A and IR-C is measurable in subjective thermal sensation in the 22 °C air temperature block, regardless of the irradiance level. In contrast, the irradiance needs to be high enough (in this case 200 W/m²) in the 16 °C air temperature block to identify a statistical effect in the thermal sensation. This outcome is somewhat unexpected when just focusing on literature on thermal comfort models, which claim the effects of IR-C and IR-A on thermal sensation to be equal (Fanger, 1970, Nilsson et al., 1997). However, it is explainable by the effects of infrared radiation spectra on skin reflectance rate and skin penetration depth (Piazena and Kelleher, 2010). Interestingly, since IR-A has a deeper penetration depth and a higher reflectance rate than IR-C, IR-C is perceived as warmer than IR-A under equal environmental conditions.

Since the results of this study show that radiation could be an effective tool for increasing thermal sensation, the results serve as basis for future technical developments. Intelligently placed heaters could increase the efficiency of an HVAC system by using demand-oriented heating and in this way yield energy-saving potential. As this study focuses on the effects of the different spectra on thermal sensation, the connection between thermal sensation and thermal comfort should be discussed in future work, as well as interdependencies between spectra, irradiance level, and air temperature on an empirical level. In this vein, additional data on physiological parameters should be analysed and interpreted additionally, in order to enhance thermal comfort models.

6.4 TME study – ambient light and fragrances as comfort moderating factors

6.4.1 Introduction

TME study considered ambient light and ambient scent as comfort factors with a within-subject design. The study took place over five days (27-28-29 of November and 3-4 December of 2018). During each day, the comfort factors were tested in a different thermal environment (steady state condition between 17.5°C and 24.5°C). In total 47 participants (at least 8 per day) joined the study and were exposed to test cases with three different scents (including "neutral" as baseline) and three different ambient light colours (including "no light" as baseline).

6.4.2 Comfort factors - stimuli considered

Ambient scent

A preliminary pilot-test has been set up in order to identify potential scents that could be implemented in the DOMUS experimentation. The aim is to understand whether a scent can enhance a sensation of comfort or, in the opposite case, spoiled it.

The experiment is conducted for a period of one hour, in two separated rooms. During the session the temperature of both rooms is set to 21°C. Two VAVA Car Diffuser are placed one in each aforementioned rooms, and a total of eight essential oils are tested.

Same concentration are used for each scent: a total of 12 droplets of essential oil are added to the diffuser, already filled with 60 ml of water.
A total of five participants were gathered outside one room. Inside, the diffuser is turned on and the first scent is released in the room. 30 seconds after the activation, participants are invited to enter the scented room and accommodated on chairs. After two minutes they were asked to fill a questionnaire. Participants were unaware of the nature of the scent.
The questionnaire take into account three factors:

- Sensation (5-point scale: from "1 - cool" to "5 - warm")
- Odour intensity scale (7-point scale: from "0 - no odour", "6 - intolerable")
- Pleasantness / Hedonic Tone (9-point scale: from "1 - very unpleasant" to "9 - very pleasant")

When questionnaires are filled participants will be asked to leave the room. In the meantime, the second room is setup in the same manner, participants are asked to move to the other room where next scent is diffused. At the end of each test, after participants have left the room, an odour remover is sprayed in the ambient and a new essential oil is poured in the diffuser. Once more, the participants are asked to move back to first room, scented with the third scent. The pilot test is repeated for a total of eight time, one for each scent. After the experiment, results have been extracted and are presented in the table below (reference):

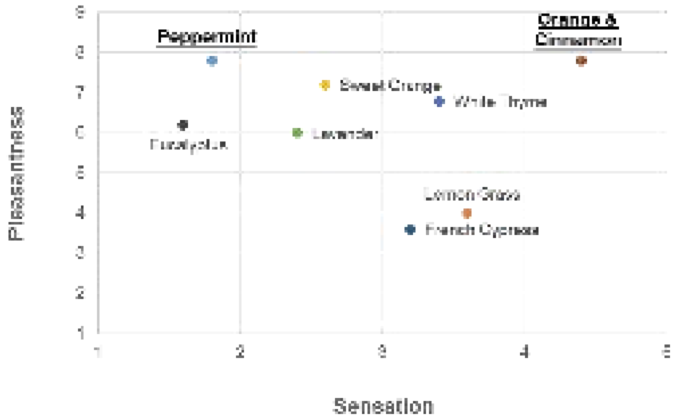


Figure 37: 8 scents mapped according to pleasantness and warm-cold sensation

Alongside their pleasantness, orange & cinnamon and peppermint have been identified as scents with the potential to provide a warm and cold sensation. They have therefore been included as scents to be tested in the TME experimentation.

The eight pilot scents have subsequently been analysed with the intention of quantifying their distinctive odours. The AromaBit sensor is an electronic device constituted of five separated chips, each presented with seven sensors, for a total of thirty-five (35) different sensors. The electronic nose senses the characteristic of a scent thanks to thirty-five (35) separated outputs detected as a frequency change in a singles electric sensors. Altogether, signals represent the digital fingerprint of a particular scent.

A principal component analysis (PCA) has been performed on the collected data. The loading plot is represented in the figure below. It has been made in order to summarize on a two-axis graph the measurements made by the 35 sensors. It displays principal component F1 versus principal component F2 representing in total 65.59% of the variability in the data (respectively 37.76% and 24.83%). Keeping in mind the representativeness of both axes, the proximity between fragrance points can be interpreted as a representation of the proximity of their related 35 sensor readings. Scatter of the points underlines the variability of single scents and their unique characteristics. It is interesting to notice that the opposite location of the two selected scents (orange & cinnamon and peppermint) on the loading plot suggests very different sensor measurements.

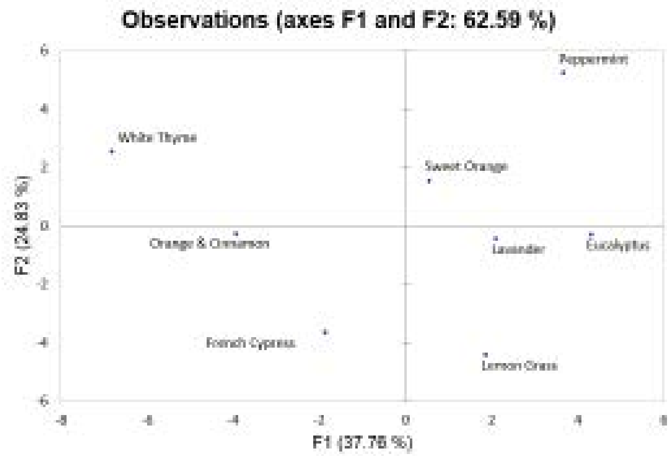


Figure 38: Loading plot from PCA of the 8 scent measured. Principal component F1 versus principal component F2

Ambient light

In order to select the ambient lightning for the TME experimentation the research has been focus around literature review. No experimentations have been carried out in a car environment but previous studies conducted in a closed environment indicate that ambient lightning can affect the perceived temperature (see D1.1).

Several studies affirm how yellow lights can provide a sensation of warm while a blue light can return a cold sensation. Two separated studies (Winzen et al., 2014) (Alberts et al., 2013) conducted in an air craft cabin illustrate how blue and yellow light indeed provide the warm/cold feeling. Huebner (2016) and Candas & Dufour (2005) illustrate in their research how a cooler to warmer light transition affects the perceived temperature in a closed room using similar hues.
In the following table light quantification of the aforementioned studies is shown:

Table 13: Ambient light colours used in other researches

	Blue	Yellow
Alberts, 2013	Centroid wavelength: 495.9 nm	Centroid wavelength: 608.0 nm
Winzen, 2014	R: 130 G: 235 B: 255 (1) R: 160 G: 255 B: 255 (2)	R: 255 G: 165 B: 0 (1) R: 255 G: 150 B: 0 (2)
Huebner, 2016	6500 K	2700 K
Candas & Dufour, 2005	5000 K	2700 K

Referring to the results of the researches, a similar path for TME has been followed. Practical tests have been carried out at Toyota Motor Europe. Some considerations have been taken into account when considering the car cabin. In order to not interfere with the peripheral vision of the driver custom LED strips have been placed in front of the driver's seat, just above the level of the pedals, and on the passenger side. Efforts have also been made in ensuring the indirect lighting of the LED, as to not disturb people's attention in the vehicle.

Combining these concepts with a trial and error approach types of blue and yellow light that could fit the car environment have been selected with the following RGB values:

- Yellow-ish ambient light [R:200, G:44, B:0]
- Blue-ish ambient light [R:0, G:0, B:255])

6.4.3Method specificities – set-up

Attention was paid to consider all factors (environmental and individual) identified by the DOMUS consortium. A description of the set-up for each factor for other factors.

Air temperature

Following the step of aforementioned researches the identification of adequate air temperatures have been chosen in the vicinity of the thermal comfort benchmark assessed by the Fanger model. From the 22°C set point the temperature have been shifted upward and downwards for a total range of 7°C.
The idea of proceeding in the surrounding of the thermal comfort model benchmark is to verify and eventually quantify how “cold” and “warm” lights and scents could impact thermal and overall comfort in different thermal conditions.

Temperature has been set for the entire day of test, varying once a day for a total of five days. The values selected are the following: 17.5°C, 19.5°C, 22.0°C, 23.5°C, 24.5°C. The temperatures have been selected from the HVAC unit of test vehicles as well as from the thermal chamber control system. The cars have been left switched on for the entire length of the test day ensuring the functionality of the air conditioning unit.

Thermal chamber: The air temperature has been controlled from the control unit of the thermal chamber. The computer has been set to activate the temperature control nine hours prior to test day.

Vehicle cabin: Before jury experimentation temperature was controlled at the three locations (head, trunk, feet) indicated in previous section. The temperature was observed homogenous between the three points. Therefore the control measure of the air temperature obtained during the jury experimentations (see below) was used in the output data.

During jury experimentation each vehicle located within the thermal chamber was equipped with two type T thermocouples located behind the central car armrests in a manner to stretch upwards by 5-10 centimetres. Internal temperature measures are displayed by a Greisinger Messtechnik - GMH3230 thermocouple checker and recorded at the beginning of each test case.
Outside test hours, cars have been switched off with the windows fully open. These has been done to ensure the same temperature between the inside of the vehicle and the thermal chamber. Thirty (30)

minutes prior to beginning of tests the two cars have been switched on with the HVAC set at the appropriate temperature before the first participant of the day.

Radiation

Thermal chamber temperatures has been set equals to the ones of the HVAC system of the car. Radiant temperature effects have therefore been neglected.

Relative humidity

Relative humidity has also been taken into account. According to protocol, controlled variable of relative humidity has been monitored between values of 30 and 70 percent. Values have been checked several times per day from a specific PC located outside the thermal chamber. The same software controls the thermal chamber temperature room. In the five days test relative humidity has been found with values ranging from 37.1 % to 48.4 %.

Air velocity

Air velocity have been measured prior to test days. Ventilation of HVAC and air vents have been carefully set up in order to not exceed the maximum air velocity allowed for the three different body parts. In order to check air velocity level a Schiltknecht - ThermoAir 3 anemometer has been utilized. Measurements of air velocity at feet, trunk and head level were found below the 0.1 m/s mark.

Table 14: Air velocity at 3 locations (TME experimentation)

Head [m/s]	Trunk [m/s]	Feet [m/s]
0.09	0.07	0.08

Air quality - CO2 concentration

TCC ELT CO_2 NDIR Module Model: B-530 has been provided by Coventry University. The device has been located in the rear seats of both cars. CO_2 concentration sensor output has been registered at the beginning of each test faced by single participant. Recorded value of CO_2 concentration were stable and appeared very low (ranging from 40 to 55 ppm).

Sound type

According to general protocol, the "Tesla_100kph. [Left][Right].mp3"sound file has been exploited. For TME a variation has been included. After two minutes a recorded voice has been added in order to help participant during his test phase deposing the task and subsequently filling questionnaire B.

According to protocol the sound pressure level: Sinus Messtechnik - 61672-1 has been utilize to ensure a maximum of 64 dB(A) as sound level output from the Sennheiser HD 25 Basic Edition headphones, also utilized in the TME experiment as recommended.

Task

Tablets Samsung Galaxy Tab 2, 10.1 have been provided at the beginning of each test case with the aforementioned headset. Mobile Tracking Task in agreement with the general protocol have been utilized. After two minutes task duration, a recorded voice invite participant to stop the task. Participants were then invited to leave the tablet on the passenger seat while filling the questionnaire in the car.

Experimental space and seating type

The experiment has been carried out in a thermal chamber room at the technical centre of Toyota Motor Europe, Zaventem, Belgium. Two Toyota CH-R hybrid vehicles, equipped with standard automotive seating made in fabric and leather, have been parked inside the space. During the sessions both cars have been kept in ready-mode. Once the ECU felt the battery charge level was low, the internal combustion engine turned on as to recharge the latter. Thus avoiding the complete drain of the battery with the consequential halt of the air conditioning during experimentation phase.

Room lighting (illuminance, colour, presence of ambient light)

The thermal chamber has been illuminated with standard Neon lamps. Three additional Neon lamps have been deployed nearby the two cars in order to provide the necessary visibility without exceeding the 800 lux permitted by the DOMUS protocol. All the illuminance was white based and in range of 3000 to 4000 K.

Screens, buttons and other sources of light inside the car have been obscured with the help of cardboard prior to test days.

LED strips have been deployed to provide indirect illumination of feet areas of driver and passenger side. They have been positioned in peripheral vision of the participants, similar to position of ambient lighting of existing production models. Turned off for baseline and on for test cases involving ambient lighting.

Picture 11: Ambient lighting used (right: blue-ish / left: yellow-ish)

Configure and custom made controlled to work under Arduino. The latter located in a box positioned behind the central armrest, easily accessible from the rear door where reconfiguration is permitted thanks to presence of buttons on the Arduino board.

Ambient scent

A custom made box has been constructed in order to house two scent diffusers. These have been filled with the two selected scents: orange and cinnamon and peppermint. Concentration of mixture reflects the ones of the pilot test: 12 droplets for 60 ml of water. The box proved necessary in order to nullify problems of leakage and avoiding possibilities of overturning diffusers by the experimenter. Furthermore, the presence of both scents diffuser guaranteed a faster set up of the new in-cabin condition for the following test case.

Picture 12: Scent diffusion set-up

In order to reset the car environment in-between test cases an odour neutralizer has been sprayed in the cabin (as suggested - Envii Bed Fresh). In the meantime, the HVAC ventilation has been increased to maximum allowed in order to ensure a faster fresh air recharge in the vehicle. This procedure lasted 2 minutes on average.

Demographic

47 participants in total: 18 females, 29 males. In accordance with DOMUS protocol. Age group distribution is represented in the table below.

Table 15: Age repartition (TME experimentation)

20-29 y.o.	46.8 %
30-39 y.o.	25.5 %
40-49 y.o.	19.1 %
50-59 y.o.	8.6 %

Clothing

In the invitation they received, participants have been suggested to wear a long sleeve shirt, standard pants or jeans and shoes. When sitting on a chair, this corresponds to the target level of 0.76 Clo (see also

Table 5: Clo values and their measurement).

Adequate clothes have been provided in case of participant's oblivion. An appropriate changing rooms have been set up outside the thermal chamber. In case of small deviation (e.g. thin layer below shirt), the corresponding clo value was recorded by the moderator using the table indicated above.

Metabolic rate

Metabolic rate of 1.2 Met have been targeted. It represent the average metabolic rate of a person conducing a car. The driving condition have been replicated, and therefore its metabolic rate, with the introduction of the task.

Additional considerations

- Cover windshield to avoid distraction: In order to help focus participants on the internal condition of the car cabin, the windshield of the two cars have been obscured with cardboard. It also helped reducing the lux levels reached from the driving position.
- The HVAC display has been fully covered, using cardboard, in order to completely obscure the temperature display to participants.
- Hygiene: to insure standard of hygiene the headphones have been cleaned after every test utilizing Sanytol multi-purpose disinfectant anti allergen wipes. Same procedure applies for the tablet.
- The rear location of the Arduino switch for the LED strips, alongside the position of the scent diffusers box, the two thermocouples and the CO_2 sensor increased the accessibility of the experimenter/organizer to all the equipment for a better and easier overview of experimental and controlled factors. Also facilitating the reset of conditions between two test cases.

6.4.4 Method specificities – design

For ambient light and scent, a 3╳3 within-subject design has been adopted (see Table 16). Each participant was exposed to a baseline test case (test case A - without light nor scent stimuli) and to 4 test cases including single light or scent stimuli (test case B to E). The order of presentation of the five test case described previously has been counterbalanced. When time allowed, two extra test cases were added for exploratory purposes (Test case F and G). Those combine light and scent stimulation and were added to have a first image about the nature of the interaction existing between respectively "cold" scent and "cold" light and "warm" scent and "warm" light.

Air temperature was treated as a between-subject variable as each participant was exposed to a single steady state thermal environment (between 17.5°C and 24.5°C).

Table 16: TME test cases

Factors investigated	Test case A	Test case B	Test case C	Test case D	Test case E	Test case F	Test case G
Air temperature	17.5°C / 19.5°C / 22.0°C / 23.5°C / 24.5°C						
Ambient light	/	Blue	Yellow	/	/	Blue	Yellow
Ambient Scent	/	/	/	Pepper-mint	Orange & cinnamon	Pepper-mint	Orange & cinnamon

6.4.5 Method specificities – procedure

The TME protocol is illustrated in the figure below. After entering the control temperature room participants undertake questionnaire A and magnitude estimation calibration. The test case takes place in the car, at the end of which questionnaire B is presented. Reset of condition in-between test cases. Questionnaire C is filled by the tester at the end of the session.

Referring to protocol flow (see 5.4.1) below are the main observations and specificities of the experimentations conducted at TME.

Before QA (changing room and consent form)

A mass mail invitation has been sent to European employees at the Toyota technical centre of TME in Belgium.

When joining the experimentation all participants read and signed an agreement consent form for the collection of personal data prepared with the support of TME legal department. If participants forgot about the dressing code adequate clothing have been provided.

Participants are welcomed inside the thermal chamber. While they get acclimatized with the temperatures. Questionnaire A is presented (paper version – as Questionnaire B and C). Temperature level remains unknown to participants for the entire duration of the test.

QA and MEC

These tasks were conducted within the thermal chamber in order for participants to get acquainted with the temperature. This preliminary phase took a maximum of 15 minutes out of the hour of test.

Test case

Participants entered the car to experience the test case with the tablet, paper questionnaire and were left in autonomy for 3 to 5 minutes.

QB

The hedonic Tone scale (9 point from “dislike extremely”, to “like extremely”) has been added in QB for TME experimentations. It was applied on the same 7 items (sensory channels and overall) that the multi-sensory comfort section of QB is based on.

Between test cases

Participant exit the car and was asked to wait in the thermal chamber. The experimenter reset the environment and took the measurements as explained in set-up section. Once this is done the procedure repeated for the next test case.

QC and MEQ

QC: As the task did not change throughout the experimentation, QC (as presented in previous section) has been presented to participant at the very end of the experimentation.

MEQ: Magnitude estimation qualification has not been implemented as it was not included in the first version of the final protocol. The implementation of the latter has been discussed after TME tests were conducted.

Participant feedback

Participants were generally interested and pleased by the initiative. Many of them asked to be informed about the results. Some of them also reported spontaneously differences in thermal perception between the different test conditions experienced.

6.4.6Relevant findings

Holistic comfort

In total, 303 test cases have been evaluated by the 47 participants. A confusion matrix was created (Figure 39) based on thermal and overall comfort scores reported by participants in QB. According to it, thermal and overall comfort scores are correlated in only 58.8% of the cases. It is also interesting to observe that only 47.5% of the test cases for which overall comfort was achieved were also reported as thermally comfortable. At the other end of the spectrum, when overall comfort was not achieved, participants felt thermally uncomfortable in only 61.9% of the cases. This shows that, at least in the experimental setup, holistic comfort is much more than thermal comfort. For a good understanding of the confusion matrix (Figure 39), it is important to note that in “comfortable” corresponds to evaluations of “like slightly” (6th on a 9-point scale) and higher, and that “uncomfortable” corresponds to evaluations of “neither like nor dislike” (5th on the 9-point scale) and lower.

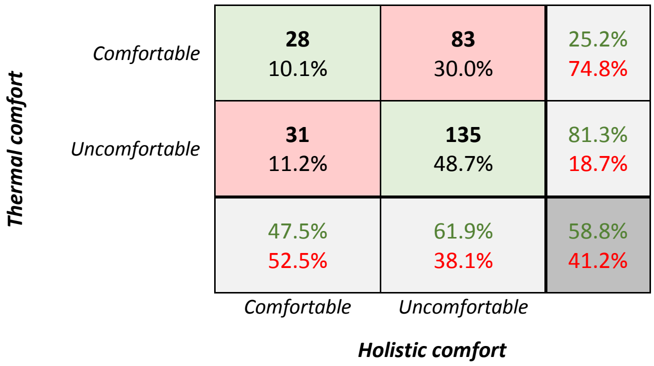


Figure 39: Confusion matrix (TME data)

Based on all participant evaluations, the overall comfort score (reported by participants in QB) has been expressed as weighted sum of each sensory comfort score (also reported in QB) using a linear regression (1). Given the coefficient of determination (R2=0.916), 92% of the variability of the dependent variable Overall (comfort) is explained by the 5 explanatory variables. Given the p-value (< 0.0001) of the F statistic computed in the ANOVA table, and given the significance level of 5%, the information brought by the explanatory variables is significantly better than what a basic mean would bring. Model parameters are presented in Table 17. The model therefore fits relatively well the comfort scores expressed by the participants in the condition of the experiment: static lab context, no extreme conditions (e.g. very cold temperature, scents commonly accepted as unpleasing). It is therefore to be interpreted with care.

Table 17: Model parameters (TME data)

Source	Value	Std error	t	Pr > |t|	Lower bound (95 %)	Upper bound (95 %)
Intercept	-4.239	1.336	-3.173	0.002	-6.868	-1.610
Olfactory	0.316	0.027	11.802	< 0.0001	0.263	0.369
Thermal	0.273	0.028	9.864	< 0.0001	0.218	0.327
Visual	0.200	0.031	6.453	< 0.0001	0.139	0.262
Acoustic	0.185	0.026	7.066	< 0.0001	0.133	0.236
Seating	0.179	0.031	5.786	< 0.0001	0.118	0.240

The results nevertheless allow to highlight the linear relationship between visual and holistic comfort as well as between olfactory and holistic comfort. Comparing their relative weight of sensory comfort components of the three variables (air temperature, ambient light colour, ambient scent), it can be observed that olfactory (dis)comfort appears to be most influential. Notably, in Bubb’s model (see Figure

5), olfactory discomfort was also presented as having the most influence on overall discomfort. The second component having the most weight appears to be thermal comfort with visual comfort placing third on this relative comparison. Acoustic and seating comfort will need complementary experimental data (planned by other partners in the DOMUS consortium), with test cases focusing on other experimental factors, in order to be discussed in the relative comparison.

Thermal sensation

Table 18 displays the overall thermal sensation reported by the participants (on a 7-point scale from -3 = "cold" to 3 = "hot") in slightly cold (19 – 21.5 °C) and slightly warm (23 - 25 °C) thermal environment. Mean and standard error of the mean (SEM) are displayed. The distinction is made between the different test conditions: exposed to "cold" and "warm" light stimulations (i.e. "blue" and "yellow/orange") , "cold" and "warm" fragrance stimulations (i.e. "peppermint" and "orange and cinnamon") and to no stimulation. Note that for both thermal environments, no significant difference in thermal sensation could be observed between the different test conditions. The observations made hereafter might therefore only serve to discuss and compare tendencies regarding their respective moderating impact. It nevertheless appears that test conditions involving "warm" stimulations (i.e. yellow light and orange and cinnamon fragrance) are reported as providing a slightly warmer thermal sensation than the ones with "cold" stimulations (i.e. blue light and peppermint fragrance) or no stimulation. Conditions involving "cold" stimulation on the contrary, were always rated colder than the baseline expect for blue light stimulation in cold environment. Therefore, these findings are in line with the small moderating effect of lighting observed in non-automotive context (no significant effect identified either). The validation of the hypotheses that "warm" stimuli tend to leads to warmer thermal sensation and that "cold" stimuli tend to leads to colder thermal sensation would nevertheless require additional studies with larger sample sizes to be fully validated.

Table 18: Overall thermal sensation reported in slightly cold and slightly warm environments

		No stim.	Fragrance		Light	
			cold	warm	cold	warm
19-21.5°C	Mean	-0.21	-0.74	-0.11	-0.16	-0.05
	SEM	*0.18*	*0.27*	*0.23*	*0.21*	*0.21*
23-25°C	Mean	0.10	-0.05	0.10	-0.10	0.25
	SEM	*0.19*	*0.15*	*0.16*	*0.24*	*0.22*

Thermal comfort

Table 19 displays the overall thermal sensation reported by the participants (on a 9-point scale from -4 = "dislike extremely" to 4 = "like extremely") in slightly cold (19 – 21.5 °C) and slightly warm (23 - 25 °C) thermal environment. Data collected outside of these boundaries were excluded from this analysis. Mean and standard error of the mean (SEM) are displayed. The distinction is made again between the different test conditions: exposed to "cold" and "warm" light stimulations, "cold" and "warm" fragrance stimulations and to no stimulation. For test conditions including sensory stimulation results are given for all participants (i.e. column "all") and well as for participant that reported olfactory (i.e. column "olf. comf.") or visual comfort (i.e. column "vis. comf."). Olfactory and visual comfort were considered reached when rated 0 ("neither like nor dislike") or higher on the 9-point scale. Note that for both thermal environments, no significant difference in thermal comfort could be observed between the different test conditions. The observations made hereafter might therefore only serve to discuss and compare tendencies regarding their respective moderating impact. It nevertheless appears that for both thermal environment considered, the presence of sensory stimuli improves thermal comfort. This observation is valid regardless of the "cold" or "warm" meaning of the sensory stimuli. Thermal comfort appears to be further improved when considering only participants who reported olfactory comfort when exposed to fragrances and visual comfort when exposed to ambient light. The assumption that "warm" stimuli tend to improve thermal comfort in colder thermal environment and that "cold" stimuli tend to improve thermal comfort in colder thermal environment is therefore not verified as this improvement is observed regardless of the stimulation.

Table 19: Thermal comfort reported in slightly cold and slightly warm environments

		No stim.	Fragrance				Light			
			cold		warm		cold		warm	
			all	olf. comf.	all	olf. comf.	all	vis. comf.	all	vis. comf.
19-21.5°C	Mean	-0.06	0.05	0.57	0.53	1.20	0.17	0.45	0.21	0.33
	SEM	*0.34*	*0.46*	*1.11*	*0.38*	*0.53*	*0.41*	*0.51*	*0.36*	*0.48*
23-25°C	Mean	0.75	0.89	1.27	1.42	1.70	0.67	0.77	0.89	1.09
	SEM	*0.31*	*0.33*	*0.45*	*0.32*	*0.52*	*0.40*	*0.54*	*0.32*	*0.49*

6.4.7 Discussion

Looking at the holistic comfort results (see 6.4.6), we observed that holistic comfort is more than just thermal comfort. They indicate that olfactory and visual (dis)comfort are two other major components of holistic (dis)comfort for the conditions tested (no extreme thermal environments). Comparing their relative weight of sensory comfort components of the three variables (air temperature, ambient light colour, and ambient scent) of the linear regression model, it can be observed that olfactory (dis)comfort appears to be most influential. From the perspective of these findings, the current trend in the automotive industry, which aims at offering a personalized cabin atmosphere by choosing from a wide range of ambient lighting colour and fragrance, appears very relevant as sensory stimuli appreciated by the user have a beneficial effect on their holistic comfort perception.

The limited interactions (i.e. no statistical difference observed) observed between visual and olfactory stimulation and thermal perception (i.e. thermal sensation and comfort) open the way to additional research on this specific topic including larger sample size. The fact that the trends observed for these interactions are beneficial to the user let us nevertheless think that the personalized cabin atmosphere features could be enhanced with context-based stimuli suggestions allowing to improve thermal perception of the user before an appropriate cabin temperature is reached (i.e. “cold” stimuli suggested in slightly warm environment and vis versa). The features detailed could also pave the way to novel energy reduction solutions balancing, from an holistic comfort perspective, the thermal comfort loss coming from a sized down HVAC unit with an improved olfactory and/or visual comfort. This improvement could be achieve with no or limited additional energy consumption: e.g. through fragrance stimulation integrated in the HVAC unit or with ambient colour achieved by changing the cabin’s screens background colour or by implementing tuneable RGB LEDs in the cabin.

6.5 ViF study – Driving activity, task load and sound quality as moderating factors

6.5.1Test cases

A study was conducted in order to investigate whether and to what extent holistic and acoustic (dis-) comfort is modulated by the 1) driving activity (manual vs. automated driving), the task load (work-inducing secondary task vs. pleasure-inducing secondary task vs. no secondary task) and the sound quality of the EV sounds. In order to test this question, a state-of-the-art simulation environment was used that ensured both high validity and control of the experiment.

Experimental design

Table 1 shows the four independent variables (IV) manipulated in the study. The first IV was the EV sound (Limousine vs. small EV), the second IV the driving condition (automated vs. manual driving). The third IV was the task load during the driving condition (work-inducing secondary task, pleasure-inducing secondary task or no secondary task), and the fourth IV the assessment environment (in vivo; i.e., assessment after a driving task vs. in vitro; i.e., assessment without additional driving task). All variables were varied within subject.

As main dependent variables the subjective acoustic annoyance as a measure of acoustic discomfort, the subjective holistic comfort and the time to holistic discomfort were assessed (see in section 5.5). Further variables of interest were the assessment of the sound quality of the two EV sounds (in-vitro assessment) and the subjective working load of the participants regarding the type of secondary task (see below).

Finally, for six participants, also the electrodermal activity (EDA) was measured during the experimental trials in order to obtain a more objective measure of the effect of task load and sound quality.

Table 20: Overview of Dependent and Independent Variables

Name	Description
Independent variables	
Vehicle Sound	Limousine, small EV
Task type	Manual driving, Automated driving,
Task load	Work-inducing secondary task, Pleasure-inducing secondary task, No secondary task
Assessment environment	Assessment after a driving task (in vivo) vs. assessment without driving task (in vitro)
Main dependent variables	
Subjective acoustic discomfort	Subjective perception of acoustic discomfort (magnitude estimation task; measured in-vivo and in vitro)
Holistic comfort	Subjective perception of holistic comfort (rating; measured in-vivo only)
Time to holistic discomfort	Subjective perception about how long it would take until the ride is experienced as uncomfortable (in minutes; measured in vivo only)
Further dependent variables	
Task load (NASA TLX)	Measure of perceived task load
Performance in secondary task	Hits during the work-inducing secondary task
Sound quality assessment	Subjective perception of the sound quality of the two EV sounds (measured in-vitro only)
Simulator sickness	(before and after simulation)

The combination of the independent variables environment resulted in four driving conditions:

- Automated driving with the concurrent work-inducing task
- Automated driving with the concurrent pleasure-inducing task
- Manual driving with the concurrent work-inducing task
- Manual driving without secondary task.

Note that automated driving without secondary task was omitted because of concerns that the participant may engage in difficult to control secondary task activities. Also, manual driving was not combined with the pleasure-inducing task because it was not possible to play a game while driving. In each of these four conditions, either the small EV or the limousine EV sound was presented, thus resulting in eight experimental trials. The combination of the independent variables was counter-balanced over the experiment to avoid any effect of order.

Study participants

32 participants were tested in this study (18 male, 14 female). They were 27 years on overage (ranging from 18 to 49 years). Half of them had experience with automated driving systems, 7 with a driving simulator. All the participants owned a valid driving license. All participants gave written informed consent.

6.5.2Set-up and protocol specificities

EV sounds

For the measurements an artificial head of the brand Head Acoustics (sensitivity, 50 mV/Pa, HSU II) was used. The data was recorded with a 24 bit front-end (SQUADRIGA II) with a sample rate of 48 kHz. Head Recorder 10.0 has been used for signal acquisition. The analyses and conclusions are based on signal processing performed with Artemis Suite 10.6 (also Head acoustics). The utilized technology is according to the current state of the art and also reviewed by ISO 9001:2015 standards.

Because the sounds were played in a simulator and needed to be attenuated with the speed of the vehicles, the recorded sounds had to be approximated by appropriate vehicle sound models. These sound models were based on recordings of two similar types of vehicles. The sound for the small EV was recorded on a Mitsubishi i-MiEV which is technically very similar to the Citroen C-0. The sound of the limousine EV was recorded in Mercedes C-class, the engine sounds isolated and modified to resemble an electric vehicle. The figure below shows the frequency characteristics of the sound pressure levels for the recorded versus simulated vehicle sounds.

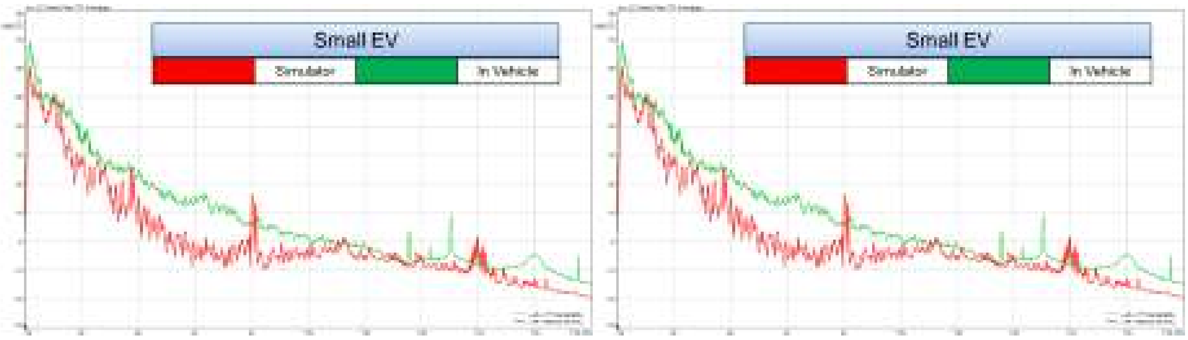


Figure 40: Small and Limousine Vehicle Sound Pressure Levels Measured versus Simulated

The SPLs for the small EV were 70 dB(A). The SPLs for the limousine EV were 64 dB(A)

The playback of the sounds occurred on the speaker system of the driving simulator, not on headsets to ensure the realistic experience of the task environment. The driving simulator also provided auditory noise through the shakers for enhanced realistic experience which would be filtered-out through the use of headsets. Therefore, headsets could not be used for this experiment. Sound levels were measured with a Larson Davis 824 precision sound level meter and adjusted to the required levels.

Both sounds used in the simulation were based on realistic acoustic sound as described in Section 5.2.7, which run in real time in the simulation software and respond to the driver inputs generating the expected corresponding motor, wind, and road noises. The sounds were played on a Logitech 7.1 sound-system. The loudness of the two vehicle sounds was held constant at 64 dB (limousine EV) and 70 dB (small EV) across the whole experiment.

Acoustic discomfort

To determine the subjective acoustic discomfort of the participants regarding the EV sounds, a magnitude estimation method with cross-modality matching is applied (Stevens & Marks, 1980). That is, the participants are asked to indicate how annoying the sound was by writing down a number and drawing a straight line which indicate the level of the subjective acoustical discomfort. A higher number and a longer line indicate more acoustic discomfort. The participants do not get any anchor value, such that they rate their subjective annoyance based on an internal scale. In order to use this method properly, the participants need an initial training phase before the experimental trials start. Furthermore, after the end of the experiment, this method requires that the participants assign given verbal qualifiers (e.g., 'good', 'bad', 'very good' etc.) to the magnitude estimation responses they provided during the experiment. In this way, it is possible to provide a linguistic interpretation to the number/line preferences about the perceived acoustic discomfort in the simulated vehicle.

Holistic comfort

Subjective comfort is measured by a questionnaire created at ViF that addresses nine aspects of holistic comfort: activity (regarding the main task and the secondary task), emotional experience, seating, temperature, air quality, smell, lighting, and overall comfort. Participants are asked to rate their perceived comfort on a 7-point scale (from [-3] "very unpleasant" to [+3] "very pleasant").

Sound-quality assessment

Sound quality of the two EV sounds was assessed with a German translation of the sound-quality assessment as described in Swart & Bekker (2014). In this scale, the sound is assessed using 12 bi-polar semantics pairs, separated by a 7-point scale (quiet-loud, calm-shrill, pleasant-annoying, deep-metallic, comfortable-uncomfortable, powerful-weak, sporty-conservative, rumbling-flat, exciting-boring, spirited-dull, effortless-strained, refined-harsh).

Comfort assessment

For the assessment of the acoustic and holistic (dis-)comfort within the driving task, the questionnaires and methods as described in section 5.6 were used. All questionnaires were provided in German.

Driving simulator

The used simulator is a static system from VI-grade with a fully functional cockpit derived from real car with two seats, active ventilation system and steering wheel torque system. The cockpit is mounted on shakers and hosts a 7.1 Dolby Surround audio system with a Brüel & Kjaer sound modelling system for the high-fidelity acoustic rendering. The visual system includes a 5m diameter vertical cylinder with three 4K-resolution projectors for a total horizontal field of view of 220 degrees. The used driving simulation software is SCANeR (AV Simulation) and VI-GraphSim was used for the vehicle dynamics model.

Picture 13: Driving simulator used in the study

Further test material
All participants filled-in an informed consent and a demographic questionnaire. In order to investigate the task load of the participants, the NASA TLX was used (see section 5.5). Furthermore, a motion-sickness scale was provided before and after the experimental trials in the simulator.

Tasks
Primary tasks:
Participants were asked to drive a vehicle in a driving simulator on a highway. The car had automatic gears, there were no intersections or stops. In the manual driving condition, participants had to adjust the vehicle's speed and to perform the necessary steering manoeuvres to maintain the vehicle on the road. In the automated driving condition, participants did not perform a primary task.

Secondary tasks:
Participants were asked to complete a work-inducing secondary task while driving. That task consisted of the SuRT [ISO12] which was presented on a tablet (Beneve; Android 7.0). In the SuRT, the participants are required to tap accurately on the biggest circle within an accumulation of smaller circles and receive points for hits/penalty points for misses. A high score for the hits is provided. The task is self-paced, as soon as a driver has made a selection, the next screen is displayed. This task is intended to increase the workload while performing a primary task like driving a car.

Picture 14: SURT - The drivers select the left side of the display where the large circle is located

As pleasure-inducing secondary task was used as alternative to the work-inducing tasks in the automated driving condition. That task consisted of participants playing a free version of the game Tetris on the same tablet as the SURT. In this game, the players arranged blocks that are entering the display area to a certain arrangement[1]. This task was intended to invoke a joyful activity to determine its impact of perceived comfort.

Picture 15: Secondary Task: Tetris game

Electrodermal activity (EDA)

Electrodermal activity was measured for the first couple of participants. Because no recognizable trends were found and the measuring equipment was not available anymore, the data collection was continued without measuring EDA.

Procedure

Each session started with a preparatory phase, followed by the in-vivo assessment in which the participants completed the eight experimental trials in the driving simulator and the assessment took place after the respective driving task, the in-vitro assessment without concurrent driving task, and the post-test phase (see Figure 41).

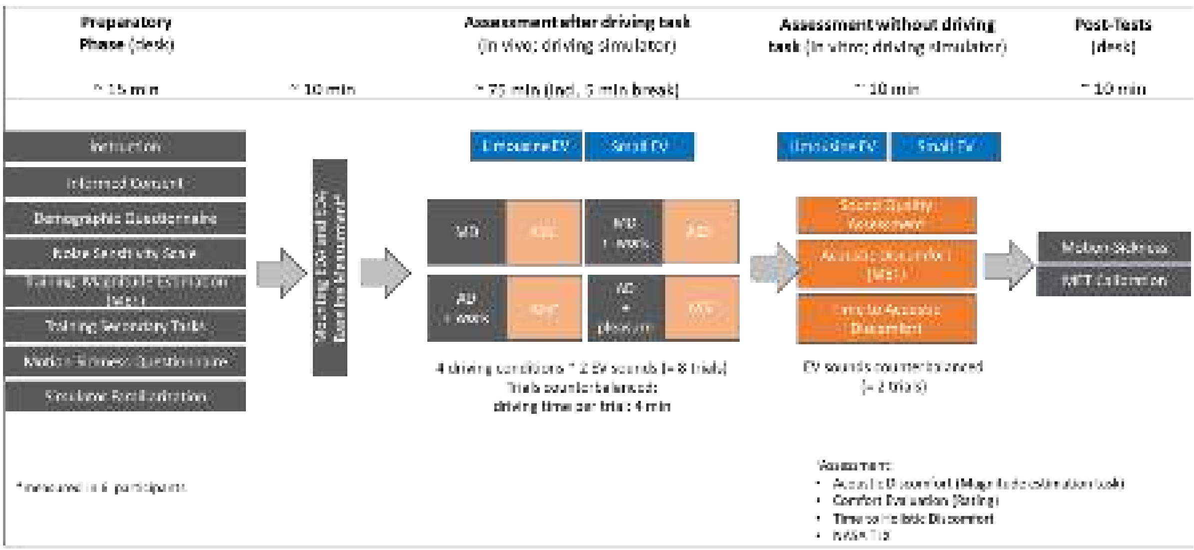


Figure 41: Overview on the experimental setup of the study. See text for details.

Preparatory phase: At the beginning of the session, the participants were informed about the procedure of the study and filled-in the consent form, the demographic questionnaire and the German version of Weinstein´s Noise Sensitivity Scale (Weinstein, 1978; Zimmer & Ellermeier, 1997). After this, the training phase of the magnitude estimation method and the familiarization with secondary tasks were carried out.

[1] https://play.google.com/store/apps/details?id=game.puzzle.blockpuzzle&gl=AT

Finally, a motion-sickness scale (Balk et al., 2013) was administered. For six of the participants, electrodermal activity (EDA) was measured during the in-vivo assessment. To this end, two electrodes were placed on the bare left inner foot and a baseline measurement (2 minutes) conducted during which the participants were asked to sit still.

The baseline measurements were followed by a familiarization phase in the driving simulator. In this familiarization phase, participants carried out simple driving manoeuvres (e.g., breaking, accelerating to and driving a constant speed, changing lanes) and were also told how to turn on the autonomous mode of the car. Critically, during this familiarization, another scenario and another sound engine (i.e. a sports car) were used than during the experimental trials.

In-vivo assessment: In the main experiment, participants completed the eight trials as described above. In every trial, the participants were asked to drive four minutes on the left-hand lane of a two- or three-lane highway. To this end, two highway scenarios were created in the driving simulator. The scenarios were counter-balanced across trials. In both scenarios, the very left lane was kept free from other traffic such that the participant did not have to perform lane changes and thus could drive at a constant speed across all conditions. In the manual driving conditions, participants were asked to accelerate to a speed of 150 km/h and to drive the four minutes constantly at this speed. In the automated driving condition, they were asked to turn on the autonomous mode of the car when reaching a speed of 150 km/h. This constant speed should ensure that sound and comfort experience were comparable across trials and participants.

On six out of eight trials, participants were required to work on a secondary task (either work- or pleasure-inducing). To this end, the tablet was placed at the co-driver's seat (automated driving) or at a mounting device which was placed to the right of the steering wheel. In both conditions, the participants were asked to start working on the secondary task by pressing the "start" button once they had accelerated to the target speed of 150 km/h. In the automated condition, they were asked to take the tablet on his or her lap when starting the task.

After each trial, the participants were required to rate the acoustic nuisance of the vehicle using the magnitude estimation task as am measure for the acoustic discomfort as described above. Furthermore, they were asked to fill in the questionnaire about several aspects of comfort (such as air-quality and temperature) and to rate their holistic comfort perception. Also, the subjective time to holistic discomfort was assessed. Finally, participants completed the NASA Task load Index to investigate the perceived workload.

In-vitro assessment: After the eight trials, the participants were asked to assess both sounds without concurrently driving in the simulator. To this end, the two vehicle sounds were presented consecutively while the participant was seated in the driving simulator and the automated mode (at a constant speed of 150 km/h) was turned on. No visual input from the driving scenario was provided which ensured that participants focused on the sound only. Participants' task was to rate the sound quality of each sound using a German version of the sound-quality assessment as described in Swart & Bekker (2014). Furthermore, they were again asked to evaluate the annoyance of each sound using the MET. For both assessments, no time limit was given.

Post-tests: At the end of the experiment, the participant again filled in the motion-sickness questionnaire. Furthermore, participants were asked to assign verbal qualifiers to the magnitude estimation responses they provided during the experiment. Each session lasted approximately 90-120 minutes.

6.5.3 Discussions

The results of the study concerning the two comfort factors that ViF investigated are here summarized for inclusion into the adaptive comfort model:

1. **Acoustic comfort factor**: The perception of acoustic stimulation in terms of comfort seems to be attenuated by the environmental context within which it is experienced. This was found by

presenting the same[2] two sounds to participants in two different environments. First in a “psycho-acoustic” environment where the participants experienced a controlled sound-presentation similar to how it is performed in psycho-acoustic experiments (see e.g. Fastl & Zwicker, 2007). Second, in a richer, more “naturalistic” environment of a driving simulator where participants experienced the whole driving task including the interior of the cabin and exterior of the vehicle via realism-approaching visual and auditory stimulation and where they performed driving tasks and secondary tasks. In such “naturalistic” environment sounds had a smaller impact on acoustic comfort than in a “psycho-acoustic” environment. For the “psycho-acoustic” environment, we found differentiation between two different sounds as an F-value of 17.9 (here the F value is of a repeated measures ANOVA dividing the variability of sound types by the overall variability) whereas in the naturalistic environment we found that F-value to be only 0.6. This represents a tremendous difference on how comparable sound levels influence the perception of comfort in different settings. This brings an important implication to the measurement of comfort in naturalistic versus laboratory settings: the context of the evaluation needs to be explicitly considered. In our case we found that impact of auditory stimulation on the perception of auditory discomfort almost 30 times less visible in a naturalistic setting. We therefore recommend the following preliminary acceptability criteria, based on a simplification of the initial simulation findings.

Table 21: Preliminary Acoustic Comfort Acceptability Criteria

	Without significant workload (or pleasurable task)	**With significant workload**
Acceptable SPL in dB(A), constant	70	64
Acceptable SPL in dB(A), variable	67	67
Frequency spectrum	TBD	TBD

2. **Task-Level Comfort Factor**: The task-level comfort factor had a significant impact on the perception of overall comfort, at least for the investigated two task-levels that consisted of a lower and a higher task-level. The higher task-level conditions consisted of participants performing manual driving while performing a secondary task. The lower task-level condition consisted of only manual driving and automated driving with a secondary task or a pleasure task. Overall comfort in the low task-level condition reached about 95 % of the experienced overall comfort in the automated driving condition (which was not significantly higher). However, in the higher task-level condition, comfort in the manual driving condition only reached 7 % (!) of the comfort in the automated driving condition (these differences also reached statistical significance). After standardization, the perceived comfort in the high-task load condition was 60 % below the comfort in the low task-load condition. This indicates clearly a strong impact of task-level on the perception of holistic comfort. We therefore suggest the acceptable comfort of high-task load driving to be 60 % below low-task load driving. In other words, as preliminary, somewhat courageous implication, automated driving should allow to lower the acceptable comfort threshold by 60 %.

[2] The sounds were presented at two different sound power levels which were the same in both environments but could not be strictly the same because the SPLs varied in the naturalistic environment according to the different driving speeds whereas in the psycho-acoustic environment they were presented at a constant level.

7 Results – Mathematical model (COV)

7.1 Approach

The holistic comfort model describes the mathematical relationship between the comfort factors given in Section 5.2, the existing thermal model and the holistic comfort. This mathematical relationship or function also establishes the basis for understanding the influence or individual contribution of each of the comfort factors toward the overall holistic comfort. The exact form and methodology for obtaining this function is detailed in the sections below. For the moment, it can be assumed that this mathematical function that describes the holistic comfort is unknown, and will be obtained as the best-performing machine learning algorithm that best explains the experimental data.

Let $\boldsymbol{F}$ be the set of all comfort factors given in Section 5.2, $\boldsymbol{c_t}$ **be an existing thermal comfort model,** and C_{hol} denote the holistic comfort sensation. The holistic comfort sensation C_{hol} is assessed on a 9-point scale, ranging from Terrible to Excellent, as shown in the table below.

Table 22: Verbal qualification (MEQ)

C_{hol}	Verbal qualification
1	Terrible
2	Very bad
3	Bad
4	Slightly bad
5	Neither Good nor Bad
6	Moderately Good
7	Good
8	Very Good
9	Excellent

The basis of the mathematical modelling is to identify a function f such that:

$$\boldsymbol{C_{hol}} = f(\boldsymbol{F}, \boldsymbol{c_t}) \qquad (1)$$

achieves a reasonably small error $\varepsilon_{\text{train}}$ on the experimental data used for training the machine learning model. As noted earlier, the holistic comfort model encapsulates an existing thermal comfort model.

To validate the correctness or accuracy of the machine learning model, the function f must as well yield a reasonably small error $\varepsilon_{\text{test}}$ on a set of the experimental data not used for training the mathematical model. In other words, the experimental data must first be divided into a training and a test set: the training set for building the mathematical model, and the test set for validating the accuracy of the model. Ideally, what is considered a reasonably small error is zero, but in the context of predicting the holistic comfort sensation of occupants, it suffices to get an error of less than 0.5, since the holistic comfort sensations differ by one-point increments. To illustrate why this is so, consider a model that gives a test error of $\varepsilon_{\text{test}} = 0.49$. If, for example, we predict an occupant's holistic comfort to be 3, then, by taking the prediction error into consideration, their true holistic comfort sensation likely lies in the range $[2.51, 3.49]$; note that any of the values in this range would still be rounded off to 3, as it would be closer to 3 than to 2 or 4, or any other comfort level for that matter.

7.1.1 Existing thermal model

The existing thermal comfort model that is employed for the holistic comfort model is the Madsen's variant of Nilsson's Equivalent Temperature model [Brusey et al., 2018]. This was selected due to the following reasons:

1) It is simple.

2) The data collected from the jury experiments does not allow an easy application of other more sophisticated thermal comfort models. Other thermal comfort models, such as Fanger's PMV and the Berkeley model, require inputs such as water vapour partial pressure, clothing surface temperature, skin external temperature, MET level, body fat, initial tissue temperature, etc. [D1.1], none of which was collected in the experimental data
3) The data from the jury experimentations reveals that holistic comfort goes beyond thermal comfort, and hence a sophisticated comfort model that provides only a thermal comfort score may not be justified.

As noted above, the holistic comfort model encapsulates an existing thermal comfort model.

The Equivalent Temperature T_{eq} is defined as [Brusey et al., 2018]:

$$T_{eq} = \begin{cases} 0.5(T_c + T_r), & \text{for } v_c \leq 0.1\text{m/s} \\ 0.55T_c + 0.45T_r + \dfrac{0.24 - 0.75\sqrt{v_c}}{1 + I_{cl}}(36.5 - T_c), & \text{for } v_c > 0.1\text{m/s} \end{cases} \quad (2)$$

where T_c is the air temperature, T_r is the radiant temperature, v_c is the airflow velocity in the and I_{cl} is the clothing insulation. The above equation for the equivalent temperature is valid for energy metabolism less than 70Wm^{-2} [Brusey et al, 2018]; it is assumed that this metabolism rate applies to all participants in the experimentations.

The Equivalent Temperature model predicts thermal comfort $\boldsymbol{c_t}$ according to the following decision criterion:

$$\boldsymbol{c_t} = \begin{cases} 0, & \text{if } T_{\text{target}} - \Delta T \leq T_{eq} \leq T_{\text{target}} + \Delta T \\ -1, & \text{otherwise} \end{cases} \quad (3)$$

where T_{target} is a target temperature, ΔT is a temperature tolerance, 0 denotes comfortable, and -1 denotes uncomfortable. T_{target} and ΔT can be defined according to the ISO standard 14505-2.

In addition to the Equivalent Temperature model, two other existing thermal models, namely, the Predicted Mean Vote (PMV) and the adaptive comfort model were also implemented for comparison.

In order to motivate the existing thermal comfort model, we first show a confusion matrix from the experimental data illustrating the discrepancies between thermal comfort and holistic comfort, which emphasises the hypothesis that there is more to holistic comfort than thermal aspects alone.

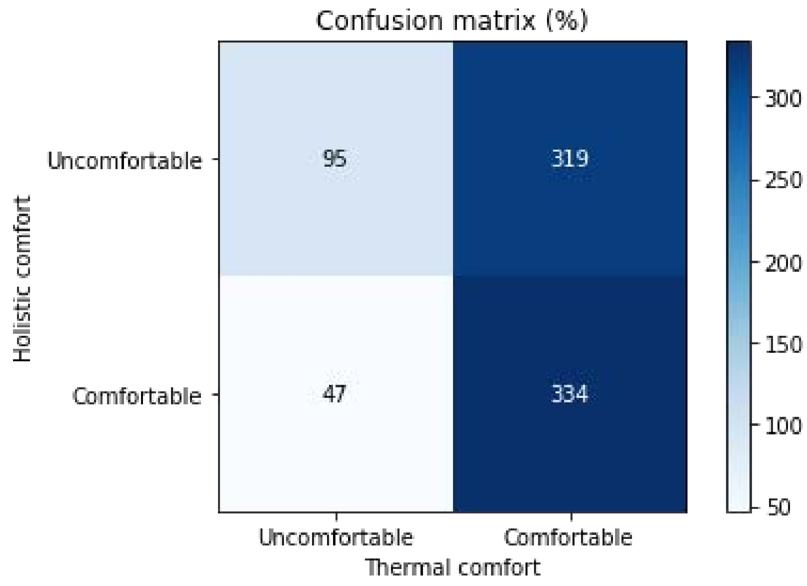


Figure 42: Correlation between thermal comfort and holistic comfort

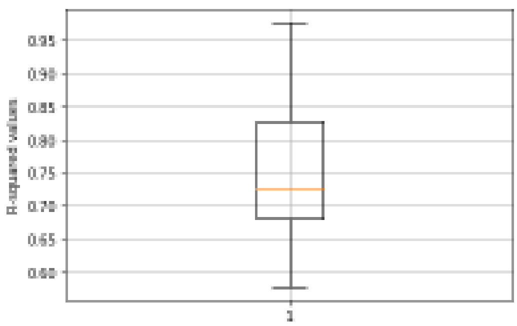
The above figure shows that when subjects report that they were comfortable holistically, in about 88% (i.e., 334/(334+47)) of the time they are thermally comfortable. However, only about 23% (i.e., 95/(95+319)) of subjects who reported that they were holistically uncomfortable, were, in fact, thermally uncomfortable. In total, only in 54% ((334+95)/(334+95+319+47)) of cases is thermally comfort correlated with holistic comfort. This suggests that other comfort factors can be manipulated in order to bring the comfort perception of car cabin occupants to an acceptable level.

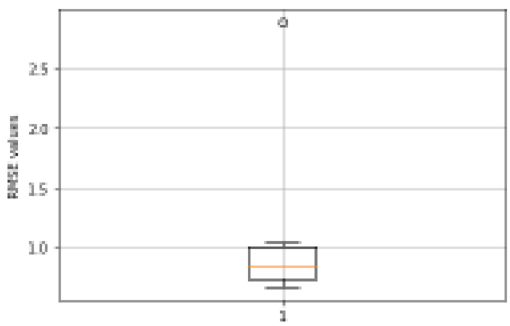
The figure further suggests that the non-thermal factors had more to do with discomfort than comfort, and that thermal comfort would likely account for half of the accuracy of any holistic comfort model.

Specifically, it was found that the holistic comfort sensation in terms of the other comfort dimensions is given by:

$$c_{holistic} = 0.399c_{thermal} - 0.012c_{acoustic} + 0.073c_{seating} + 0.209c_{visual} + 0.356c_{olfactory} - 0.092 \qquad (4)$$

with a cross-validated mean R-squared value of 0.748 mean RMSE of 1.05 on a 9-point scale. These are shown in the figures below:





Even though, Equation (4) does not show the influence of the actual comfort factors, it shows mathematically the relevance of the other comfort factors, notably olfactory and visual comfort to the holistic comfort sensation.

7.1.2 Combining datasets

Different experimental partners varied one or more comfort factors in order to determine how they affect the holistic comfort perception. In this manner, it was anticipated that the data collected from the different jury experimentations may be combined to form one large experimental data, following the Excel template provided by TME. However, the data collected by different partners are fundamentally different, to the extent that they do not allow combination in a straightforward manner; consequently, the significance of the results of the holistic comfort modelling is diminished. In the following, we show how the different datasets vary. Following that, we show the different ways in which the datasets may be combined. Then, using a simple linear model, we show the expected accuracy of the holistic comfort model that can be developed using those datasets.

TME

This dataset contains all the comfort factors, as well as all the holistic comfort perceptions. However, the dataset does not include the subjective verbal qualifiers (Magnitude estimation – qualification) that describe the line lengths and numbers. The effect of this omission is that it is impossible to relate the comfort factors to comfort perceptions on the scale of "Terrible" to "Excellent". Consequently, there is no output y with which we can train the holistic comfort model.

In the absence of these verbal qualifiers, we have utilized the "hedonic tone" – a set of extra columns provided by TME – which are given on a scale of -4 (Extremely dislike) to 4 (Extremely like) to be representative of the verbal qualification of the occupant's comfort to some degree.

CRF

This dataset had some missing columns from the template, but the ambiguity has since been resolved. This dataset now has all the relevant comfort factors (and additional factors in terms of some HVAC settings), the holistic comfort perceptions, and the subjective verbal qualifiers. Thus, there are no issues with this dataset.

COV

This dataset has all the relevant comfort factors (and an additional comfort factor in terms of the heartbeat rate), the holistic comfort perceptions, and the subjective verbal qualifiers. However, the airflow speeds are given in terms of the voltage output of the sensors employed, and are yet to be converted to m/s. TME have recently provided experimental calibration data and thus this issue should soon be resolved.

VIF

This dataset contains all the subjective verbal qualifiers for the holistic comfort perceptions, even though:

1) Only the line lengths were recorded, except for acoustic dimension that had both a line length and an associated number. Thus, only the line lengths can be used to relate to the verbal qualifiers, instead of the line lengths and the associated numbers.
2) Some line lengths contain negative values. It is possible that for holistic comfort perception other than sound, a -3 to +3 scale was used.

While this dataset contains additional comfort factors such as the drive type, the main problem with this dataset is the set of other comfort factors that are missing, among them:

i. Height
ii. Weight
iii. Clothing insulation
iv. Temperature/ activity history
v. Temperature sensitivity
vi. Radiant temperature
vii. Airflow velocity
viii. Relative humidity
ix. Lux level

It is worth noting that interpreting the holistic comfort perception given as the line lengths in terms of the verbal qualifiers yield only three holistic comfort levels in VIF's dataset: Terrible, Very good and Excellent.

IKA

Due to safety and methodological reasons, participants had to be blindfolded in each experimental condition during the experiments. All relevant subjective comfort perception, therefore, was assessed verbally via interview using a scale from 1 (not comfortable) to 10 (very comfortable). This means there are no written subjective qualifiers (magnitude estimation – qualification) regarding light colour, visual nor acoustic comfort in the dataset of ika. The assessment of visual comfort was not applicable, because visual perception was hindered. The same is true for the acoustic perception as the auditory modality was frequently occupied by the auditory secondary task (every 3 seconds an artificial voice spoke a number) and the experimenter asking questions (every 60 seconds the participants were asked for a thermal sensation and comfort vote). Neither visual information processing took place nor acoustic comfort perception was possible due to the overshadowing presence of the artificial voice and the occupancy of the secondary task. The focus lies on the assessment of thermal sensation and thermal comfort.

Through statistical transformation, all relevant data assessed by ika can be implemented in the holistic comfort model, but must be interpreted with care, due to the differences in assessing the comfort perceptions (written vs. interview). This limits the predictive strength of the holistic comfort model slightly.

7.1.3 Holistic comfort modelling as a regression problem

While the response variable of interest C_{hol}, has categorical values, it is inappropriate to treat the problem of predicting the holistic comfort as a classification problem. This is because many classification algorithms minimise error metrics such as the 0-1 loss, or the sparse categorical cross-entropy, which tend to consider the following two errors equivalent:

1. The error in predicting a comfort score of 3 (Bad) as 4 (Slightly bad)
2. The error in predicting a comfort score of 3 (Bad) as 9 (Excellent)

However, for our purpose an error in the first instance would be desired.

On the other hand, since the categories are ordinal (i.e., 7 is greater than 6 in the sense that Good is more comfortable than Moderately good), this allows the problem to be cast as one of regression. However, since regression may yield some real-valued outputs that may be outside the set of comfort perceptions given in Table 22, the output of the regression needs to be rounded and bounded in the range [1, 9], as given in Table 22.

7.1.4 Holistic comfort modelling as a classification problem

Since the assessment framework in Deliverable D1.2 requires that the holistic comfort score be binary, we may yet think of the holistic comfort modelling as a classification problem. To do achieve this, we may arbitrarily choose a threshold, e.g., 4, so that any comfort level corresponding to "Slightly bad" or better is considered as "Comfortable" (0), while anything worse than "Slightly bad" is considered as "Uncomfortable" (-1). This is given in Equation 2 as:

$$C_{bin} = \begin{cases} 0, & \text{if } C_{hol} \geq 4 \\ -1, & \text{if } C_{hol} < 4 \end{cases} \qquad (2)$$

where C_{bin} is the binary holistic comfort score.. Ultimately, we seek a relationship between the binary holistic comfort C_{bin} and the comfort factors $\boldsymbol{F}$.

This threshold may be varied in order to obtain the optimal balance between comfort and energy consumption.

7.1.5 Methodology in training holistic comfort model

This subsection details the methodology used in training the holistic comfort model. More details about this methodology can be assessed from the accompanying Python notebook used for running the holistic comfort model scripts.

A. Data preprocessing

1. The datasets from all experimental partners were combined. The combined dataset amounted to about **1238** data rows.
2. This combination involved many different manipulations, in particular ensuring that all keys such as gender, “yes” or “no” binary responses, categorical values such as scent types, and how missing values were recorded – were of the same form and case.
3. Some noise sensitivity assessment values appeared in the wrong columns for some datasets and were corrected.
4. To make the datasets consistent, “magnitude estimation – qualification” values for some partners had to be restated on some bounded intervals, e.g., [1, 10] for one experimental partners, and [-4, 4] for another.
5. In one instance, hedonic tones that assess how participants like or dislike the different comfort dimensions – are used as proxies for the verbal qualifiers of their comfort scores, in the absence of their verbal qualifiers.

B. Common comfort factors

6. Next, since the different experimental partners did not collect data for all the comfort factors, the common comfort factors are extracted to use as inputs to the holistic comfort model. The following are the factors that were common to all experimental partners, together with their summary statistics in Table 23:

Table 23: Summary statistics of common comfort factors

Comfort factor	Mean value	Standard deviation	Minimum value	Maximum value
Air temperature (trunk)	22.5	3.3	15.0	40.3
Sound level	64.4	2.3	61.3	70.0
Sound type	78% baseline, 11% Limousine, 11% small EV	NA	NA	NA
Age	36.6	12.5	18.0	69.0
Gender	51% males, 41% females	NA	NA	NA
Noise sensitivity (Q4.8)	-0.3	1.4	-2.0	2.0
Noise sensitivity (Q4.18)	-0.1	1.6	-2.0	2.0
Task load – mental demand	-4.1	4.6	-10	10
Task load – physical demand	-6.7	3.6	-10	10
Task load – temporal demand	-5.1	4.6	-10	10
Task load – performance	-3.9	4.8	-10	10
Task load – effort	-4.6	4.4	-10	10

Task load – frustration	-3.0	6.6	-10	10

7. We then remove all rows containing missing values.

8. The correlation between these comfort factors are shown in Figure 43 below, where a value of 1 shows very high positive correlation, 0 shows no correlation and -1 shows very high negative correlation:

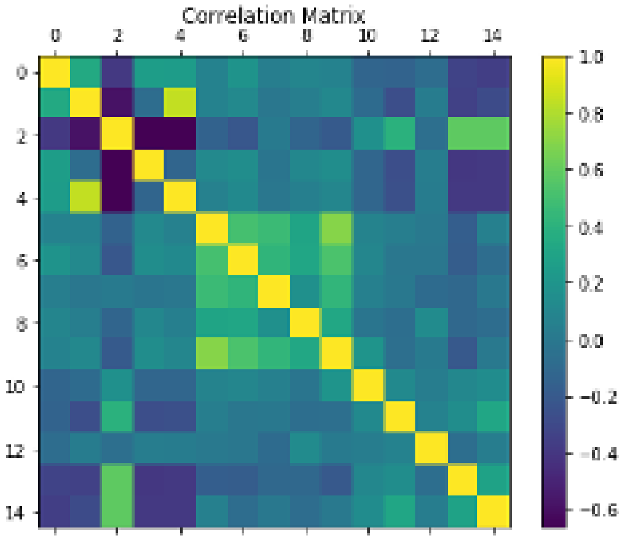


Figure 43: Correlation between comfort variables

The above plot shows that the variables or comfort factors show a fair bit of cross-correlation in the off-diagonal elements, i.e., the features are correlated, and would thus benefit from feature extraction or feature reduction methods.

C. Magnitude estimation

9. The next step involves converting the line lengths and numbers collected during the test cases to their qualitative equivalents, i.e., [Terrible, ..., Excellent] in order to get output holistic comfort perceptions for the holistic comfort model. This matching is done by first training a linear regression model for each participant entry, where the predictors are the line lengths for thermal, acoustic, olfactory, lighting, seating and holistic that were collected during the magnitude estimation – qualification phase, and the response variables are the comfort perceptions: [Terrible, Excellent] – which are interpreted on an ordinal scale of 1 to 9. Then, this linear model for each participant entry, is used to predict the holistic comfort on the scale 1 to 9, for any holistic line lengths recorded in the test cases for that participant. The figure below in Figure 44.

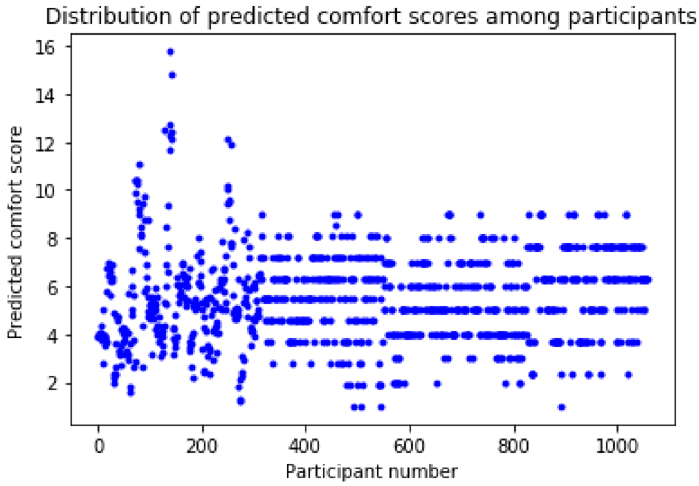


Figure 44: Distribution of predicted comfort scores

Since the output of a linear regression model is not bounded, it is to be expected that some of the predicted scores fall outside the range [1, 9]. These outlying values are clipped in the range [1, 9] prior to training the holistic comfort model.

D. Binary holistic comfort

10. In order to obtain a binary output for the holistic comfort score, we use a threshold of 5.5, so that any predicted comfort below 5.5 is considered as "Uncomfortable", and anything greater or equal to 5.5 is considered as "Comfortable". Note that this threshold may be varied in order to obtain an optimal tradeoff between comfort and energy consumption. This leads to the following distribution of comfortable and uncomfortable instances

    Comfortable count = 489
    Uncomfortable count =569

E. Training and validation

11. We then split the combined datasets into training and validation folds using K-Fold cross validation. Here, we use K=10. This implies that the dataset is split into 10 folds, nine of which is used for training the model, and the model's performance is tested on the tenth fold. Since there are ten ways of taking 9 folds out of 10, this validation methods allows for the testing of the model on 10 different test sets.

12. Prior to training the model, we normalise the input comfort factors by standardisation or mean normalisation given as:

$$f_{i,s} = \frac{f_i - \bar{f_i}}{s_i}$$

    where the ith comfort factor f_i is divided by the mean $\bar{f_i}$ and the standard deviation s_i.

    We do not implement any explicit feature reduction methods such as principal components analysis (PCA), since PCA tends to complicate the influence of the different comfort factors on the holistic comfort perception. Instead, we include regularisation terms in the machine learning models employed to reduce the effect of overfitting due to correlated or irrelevant features.

13. We then train the following machine learning classification models: two linear models – linear discriminant analysis (generative model) and logistic regression (discriminative model) – and one non-linear model in the form of a radial basis function network, which is a neural network with

one input layer, one hidden layer and one output layer, and radial basis function activation units. The choice of these three models was motivated by simplicity and explainability.

14. The classification accuracies of these models are shown below in Figure 45 below:

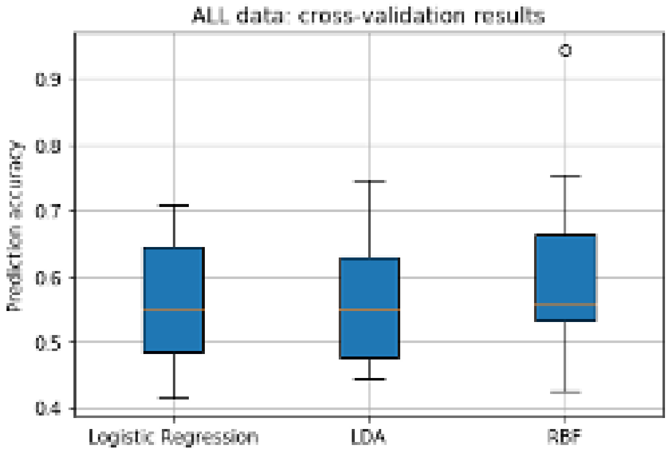


Figure 45: Cross-validation accuracy in predicting binary holistic comfort. Mean values are 56% for logistic regression, 56% of linear discriminant analysis, and 61% for the radial basis function network.

15. Note that, as the discriminating threshold (in this case set to 5.5) is varied, the classification accuracy varies. Specifically, if we moved the discriminating threshold upwards toward 9 (Excellent comfort), there would be very few instances where occupants comfort score exceeds this threshold of 9, thus, they would be few instances where occupants indicate they are holistically comfortable, and many more instances of discomfort. In this case, a naïve classifier that simply predicts "Uncomfortable" would achieve very good accuracies, but at the expense of missing out the cases where occupants are comfortable. Similarly, if we moved the discriminating threshold toward 1 (Terrible), there would be many instances where the holistic comfort score exceeds this threshold of 1, thus a naïve classifier that simply predicts "Comfortable" would achieve high accuracies, but at the expense of missing out the cases where occupants are uncomfortable. A metric that is used to test the robustness of the model under varying discriminating thresholds to show that the model is better than such a naïve model as described above is the area under the receiver operating characteristics curve, known simply as the AUC. (Area Under Curve) An AUC of 1 shows that the model correctly classifies all samples under varying levels of the discriminating threshold; an AUC of 0.5 is the performance of a random guess; and AUC of less than 0.5 corresponds to a model that is worse than random guess. The AUC is bounded between 0 and 1. The AUC performance of the three models are given below in Figure 46.

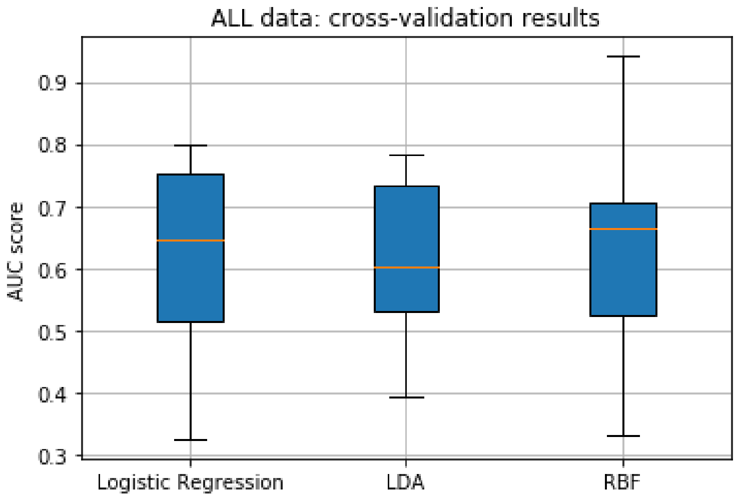


Figure 46: Cross-validation AUC performance in predicting binary holistic comfort. Mean values are 62% for logistic regression, 61% of linear discriminant analysis, and 63% for the radial basis function network.

7.1.6Model explainability in terms of feature importance

The best performing machine learning model was the radial basis function network, both in terms of the classification accuracy and the AUC score. One reason why the radial basis function outperforms the linear model is the fact that participants could register thermal and overall discomfort at temperatures that are too low just as readily as for temperatures that are too high, which suggests that the shape of the decision boundary in determining comfort is more likely to be non-linear (e.g. quadratic) in nature with increasing comfort values either side of some centrally located optimal temperature.

The radial basis function architecture can be summed up as follows:

$$\boldsymbol{f}_{\boldsymbol{A}}(\boldsymbol{F}) = \sum_{k=1}^{K} w_{Ak}\, e^{-\beta_k \|\mathbf{F}-\mu_k\|^2} + w_{A0}$$

and

$$\boldsymbol{f}_{\boldsymbol{B}}(\boldsymbol{F}) = \sum_{k=1}^{K} w_{Bk}\, e^{-\beta_k \|\mathbf{F}-\mu_k\|^2} + w_{B0}$$

where $\boldsymbol{f}_{\boldsymbol{A}}(\boldsymbol{F})$ and $\boldsymbol{f}_{\boldsymbol{B}}(\boldsymbol{F})$ are the two outputs of the network, and one decides “Comfortable” if $\boldsymbol{f}_{\boldsymbol{A}}(\boldsymbol{F}) < \boldsymbol{f}_{\boldsymbol{B}}(\boldsymbol{F})$, and decides “Uncomfortable”, if $\boldsymbol{f}_{\boldsymbol{A}}(\boldsymbol{F}) > \boldsymbol{f}_{\boldsymbol{B}}(\boldsymbol{F})$,
$\boldsymbol{F}$ is the vector of comfort factors, after they have been standardized,
$\mu_k, w_{Ak}, w_{Bk}, w_{A0}, w_{B0}\ \beta_k$ and K are model parameters that are learned during training of the radial basis function model.

The parameters of the radial basis function network are given below:

$$K = 8$$

$$w_{A0} = 0.367$$

$$w_{B0} = 0.512$$

w_A = [-0.264, 0.243, 0.607, 0.472, -0.320, 0.637, -0.504, -0.504]

w_B = [0.414, -0.128, -0.521, -0.354, 0.429, -0.502, 0.601, 0.574]

$\boldsymbol{\beta}$ =[0.022, 0.041, 0.059, 0.058, 0.043, 0.035, 0.082, 0.082]

Table 24: Mu parameters for radial basis function network

Comfort factor	μ_1	μ_2	μ_3	μ_4	μ_5	μ_6	μ_7	μ_8
Air temperature (trunk)	0.864308	-1.521022	0.715225	-0.188761	-0.149457	-0.355192	0.566142	0.685408
Sound level	-0.083641	-0.083641	-0.083641	-0.083641	-0.083641	-0.083641	2.890046	-0.083641
Sound type - baseline	-2.551825	0.391876	0.391876	0.391876	0.391876	0.391876	-2.551825	-2.551825
Sound level - limousine	3.729108	-0.268161	-0.268161	-0.268161	-0.268161	-0.268161	-0.268161	3.729108
Sound level – small EV	-0.265908	-0.265908	-0.265908	-0.265908	-0.265908	-0.265908	3.760699	-0.265908
Task load – mental demand	0.765725	0.088289	1.443161	-0.589147	-1.266583	1.217349	-0.363335	-0.137523
Task load – physical demand	0.865090	-0.323669	1.459469	-0.026479	-0.918048	0.865090	-0.026479	0.270710
Task load - temporal demand	0.266430	-0.618423	1.372496	-0.397210	-1.060849	0.930069	-0.397210	-0.618423
Task load - performance	-0.395490	0.868489	0.657826	-0.606154	-0.395490	0.447163	-0.395490	-0.395490
Task load - effort	0.232600	-0.743859	1.697287	-0.255629	-1.232088	0.964944	-0.255629	-0.011515
Task load - frustration	-0.311694	-0.755069	0.131680	-0.459486	0.870638	0.279472	-0.607277	-0.902860
Age	0.038735	0.595023	-0.279144	-0.914902	0.595023	0.197675	-0.914902	-0.914902
Gender	-0.781976	1.278812	-0.781976	-0.781976	1.278812	-0.781976	-0.781976	-0.781976
Noise sensitivity – Q4.8	-1.345413	0.843656	-0.615723	0.113966	0.113966	-0.615723	-1.345413	-1.345413
Noise sensitivity – Q4.18	-1.364863	0.585331	0.585331	-0.064734	0.585331	1.235395	-1.364863	-1.364863

While the radial basis function model can learn non-linear decision boundaries making it preferable to linear models such as logistic regression in classification tasks, the main strength of the radial basis function is in its relative interpretability of feature importance as compared to deeper neural networks.

Specifically, for any comfort factor of interest, f_i, its sensitivity to increasing holistic comfort perception is given by:

$$\frac{\partial f_{\boldsymbol{B}}(\boldsymbol{F})}{\partial f_i} = \sum_{k=1}^{K} -2\beta_k w_k \, e^{-\beta_k \|x-\mu_k\|^2} (x_i - \mu_{ki})$$

The sensitivity of the comfort factors are not constant, unlike in a linear model, but are functions of the instantaneous values of the comfort factors. That is, if, for example, the air temperature is 25 degrees, the comfort factors that would be most sensitive to comfort perception would differ from if the air temperature were 22 degrees. In the associated Python notebook, we have employed a number of prototype vectors of comfort factors at which values we are able to assess the sensitivity of the different comfort factors.

Thus, this model presents a principled methodology for adjusting comfort factors at any point in time in the car cabin, in order to ensure passengers' holistic comfort.

7.2 Relative performance of the baseline comfort model

The above results arise from many comfort factors being excluded in order to obtain self-consistent data that allows the combination of the datasets from all experimental partners.

Here, we implement Madsen's variant of the Equivalent Temperature model which requires the following parameters:
1) Air temperature
2) Radiant temperature
3) Airflow speed
4) Clothing insulation

In section 7.1, the comfort factors that are common to all partner datasets were used to train the holistic comfort model. However, these common factors given in Table 23 do not include a comprehensive set of factors that enable the implementation of the existing thermal comfort model. In particular, airflow velocity, radiant temperature and clothing were not included in VIF's dataset, while COV's data for airflow speed were inaccurate, due to malfunctioning sensors.

Thus, we modify the methodology in Section 7.1.5, by dropping data rows belonging to VIF and COV in Step 1 in order to obtain comfort factors that allow implementation of the equivalent temperature model. After removing data from COV and VIF, we are left with 911 data instances, which represent ~74% (roughly three-quarters) of the combined dataset.

The following comfort factors are shared among the three remaining experimental datasets:

1. Air temperature (head, feet, trunk)
2. Radiant temperature (head, feet, trunk)
3. Airflow speed (head, feet, trunk)
4. Clothing level
5. Indoor temperature
6. Outdoor temperature
7. Humidity
8. Temperature on day of experiment
9. Temperature sensitivity
10. Noise sensitivity
11. Lux level
12. Light colour
13. Sound level
14. Scent type
15. Task load
16. Age
17. Gender
18. Height
19. Weight
20. Q2.1 and Q2.2

It is worth noting that some of these comfort factors are categorical, and are converted into dummy variables using one-hot encoding.

After removing rows containing missing values, the equivalent temperatures are computed from this subset of the partner datasets as given by Eq 2 in Section 7.1.1, and the distribution are shown below in Figure 47A, 47B, 47C and 47D.

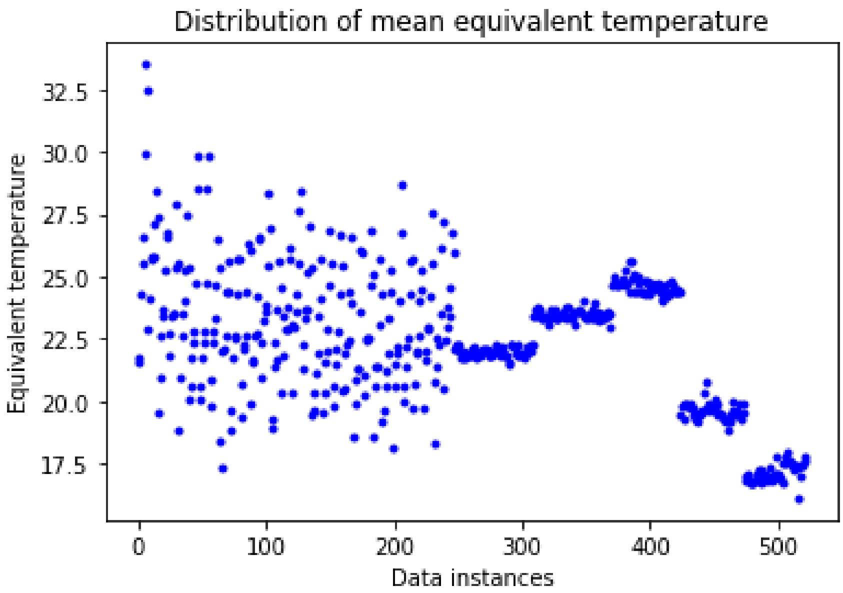


Figure 47A: Distribution of mean equivalent temperatures

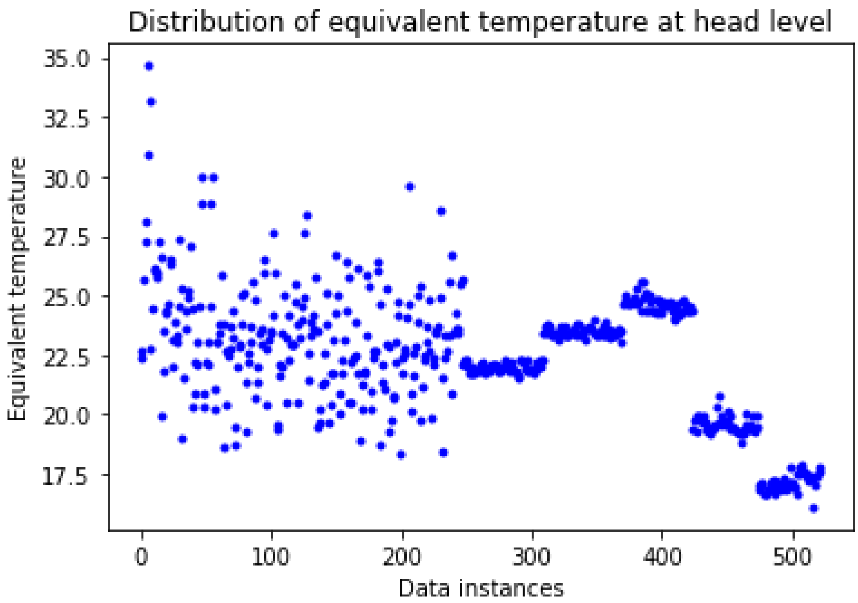


Figure 48B: Distribution of equivalent temperatures at head level

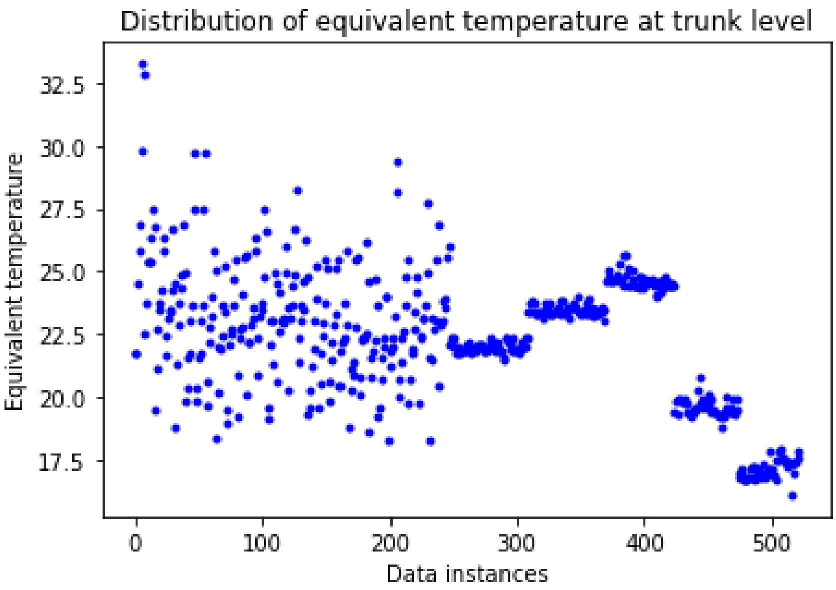


Figure 49C: Distribution of equivalent temperatures at trunk level

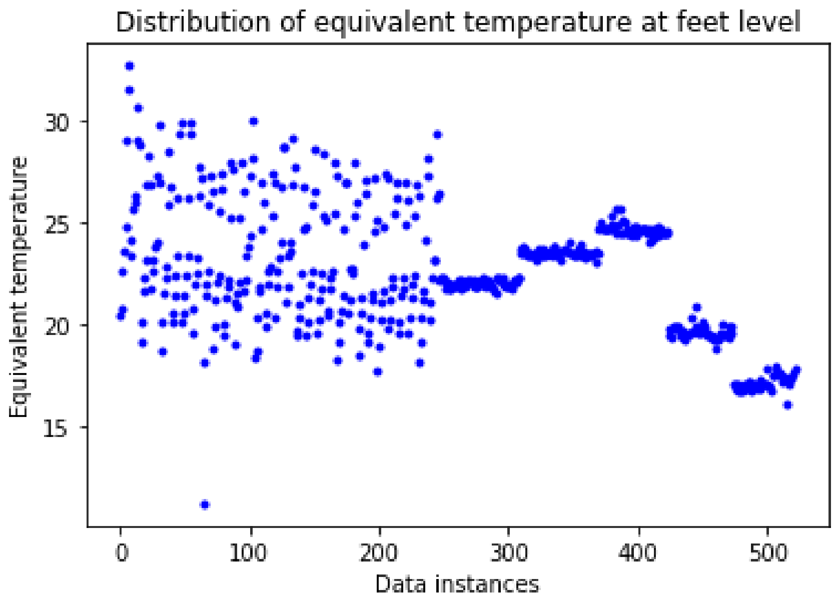


Figure 50D: Distribution of equivalent temperatures at feet level

The correlation between the equivalent temperatures at the head, trunk and feet levels are shown below:

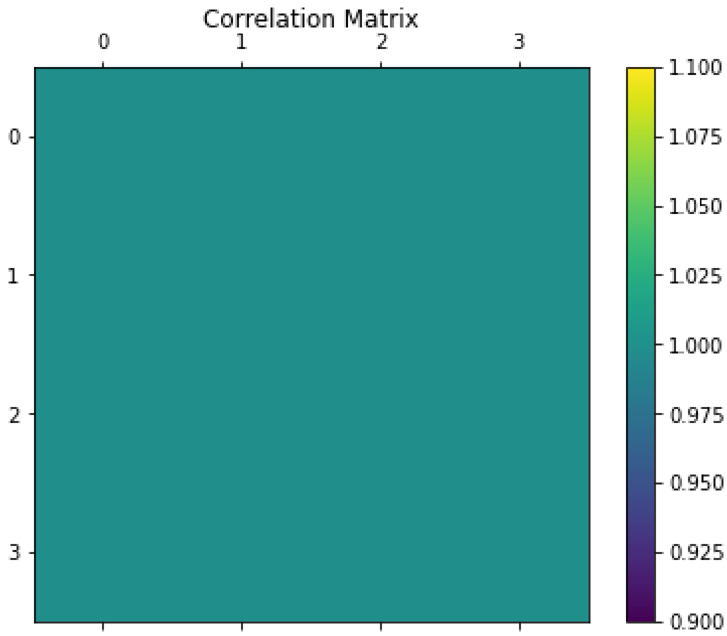


Figure 51E: Correlation of equivalent temperatures at head, trunk and feet levels

Figure 47E shows that the equivalent temperatures at the head, trunk and feet levels as measured in the experimental works are almost perfectly correlated. Thus, the data does not correspond to test cases such as those where the head region might be hot while the feet is cold.

One important observation from the above plot is the fact that some equivalent temperature values are too discrete to be the result of measurement, and seem to suggest some methodological deficiencies in the experimentation procedures.

By using Eqn 3 in Section 7.1.1, we get the binary thermal comfort $\boldsymbol{c_t}$ on the equivalent temperatures with the following distribution

Thermally comfortable count = 307
Thermally uncomfortable count =587

The binary thermal comfort output $\boldsymbol{c_t}$ is then included as part of the predictors to train the holistic comfort model. The remaining set of features show strong cross-correlation among them as shown in Figure 52:

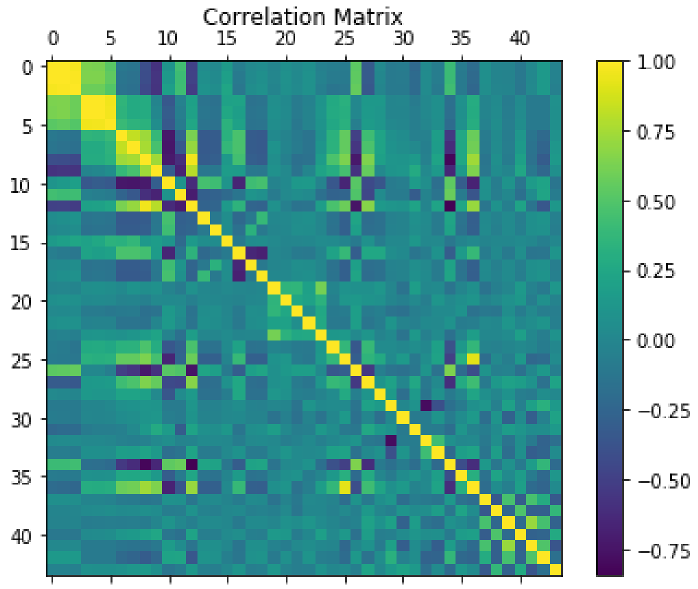


Figure 52: Correlation between comfort factors

The resulting classification accuracies are shown in Figure 53 for 5 different machine learning models, namely:

a. Logistic regression
b. Linear discriminant analysis
c. Radial basis function network
d. Random forest
e. Support vector machine
f. Deep neural network

In addition to the above machine learning models, the following existing thermal comfort models were also implemented and included in the results:

a) Madsen's equivalent temperature model
b) Predicted Mean Vote (PMV)/ Predicted Percentage Dissatisfied (PPD) model
c) Adaptive thermal model

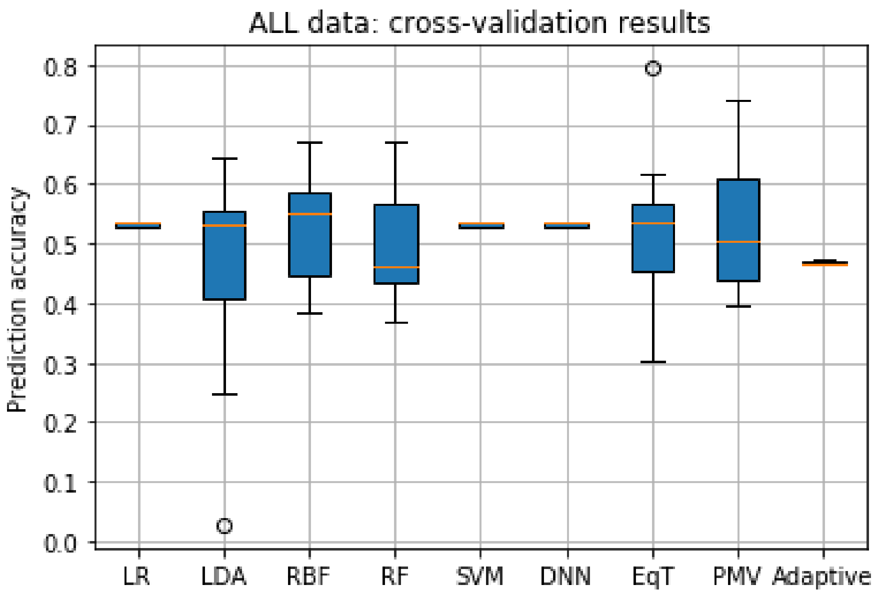


Figure 53: Cross-validation classification accuracies; mean values are: Logistic regression (LR) = 53.2%; Linear discriminant analysis (LDA) = 44.7%; Radial basis function network (RBF) = 52.8%; Random forest model (RF) = 50.0%; Support vector machine with radial basis function kernel (SVM) = 53.2% Deep neural network (DNN) = 53.2%; Existing thermal comfort model based on equivalent temperature (EqT) = 52.2%, PMV = 52.7%, Adaptive Thermal Model = 46.8%.

Three things are worth noting from the classification results in Figure 53:

1. The existing thermal comfort model based on Equivalent Temperature predicts holistic comfort correctly only about 52% of the time, i.e., only marginally better than random guess. This is in line with the observation in Section 7.1.1 in Figure 42, where it was shown that thermal comfort correlates with holistic comfort only 54% of the time.
2. The machine learning models do not perform significantly better than the equivalent temperature model.
3. Even more, the performance of linear discriminant analysis, logistic regression and the radial basis function network are lower than the results obtained in Figure 45 in Section 7.1.5. This is due to a number of reasons:
    - i. By removing data belonging to COV and VIF, there is not as much data used for training the model, hence the resulting model does not have as much predictive strength.
    - ii. By including many more comfort factors, there is an increased risk to overfitting, even though regularisation is employed in the machine learning models.

The AUC performance is also shown in Figure 50:

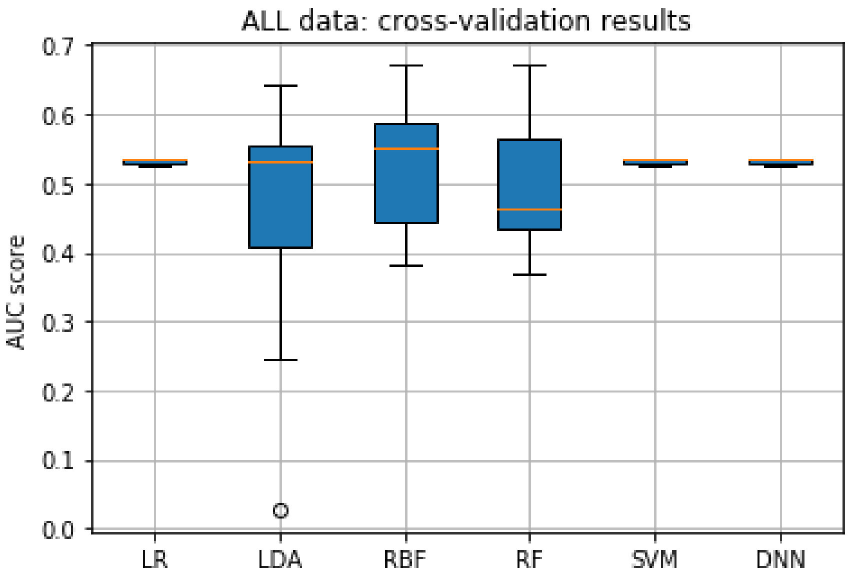


Figure 54: Cross-validation AUC scores; mean values are: Logistic regression (LR) = 0.500; Linear discriminant analysis (LDA) = 0.442; Radial basis function network (RBF) = 0.488; Random forest model (RF) = 0.449; Support vector machine with radial basis function kernel (SVM) = 0.480; Deep neural network (DNN) = 0.501

The figure above also shows that the AUC performance is also no better than random guess.

7.2.1Holistic comfort model without validation

If validation is not required, i.e., if the holistic comfort models were trained and tested on the same datasets, fig. 51 below shows the performance of the machine learning models:

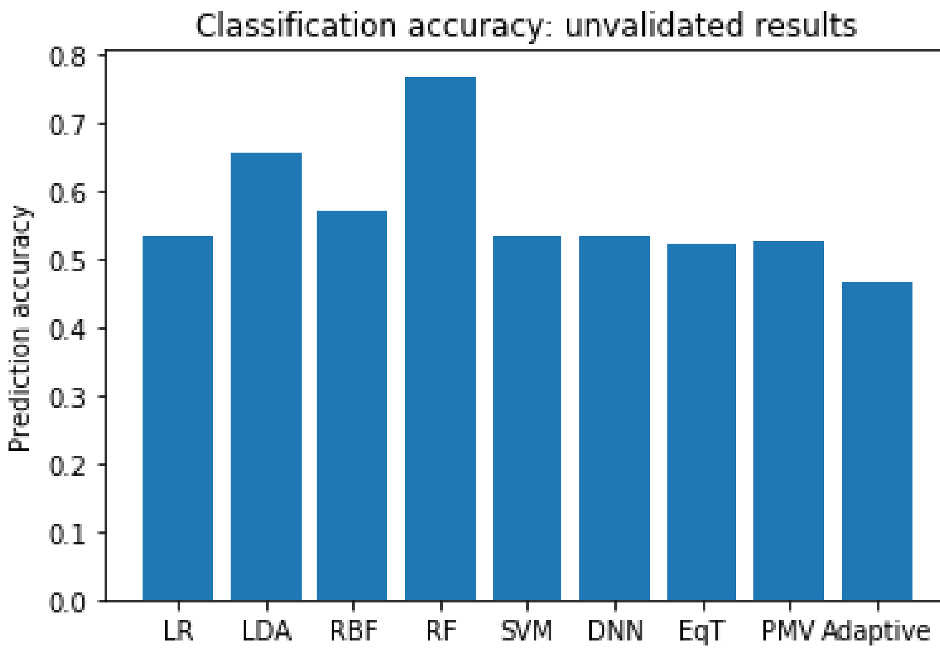


Fig 51: Non-validated classification accuracies; mean values are: Logistic regression (LR) = 53.2%; Linear discriminant analysis (LDA) = 65.7%; Radial basis function network (RBF) = 57.0%; Random forest model (RF) = 76.9%; Support vector machine with radial basis function kernel (SVM) = 53.2% Deep neural network (DNN) = 53.2%; Existing thermal comfort model based on equivalent temperature (EqT) = 52.3%, PMV = 52.7%, Adaptive Thermal Model = 46.8%.

While these models have relatively good performance and may be interpreted to understand feature importance, they are not generalisable, and are not guaranteed to predict the holistic comfort with any reasonable accuracy better than random guess.

However, in terms of feature importance, Tabe 24 below shows the most important features than explain the holistic comfort as estimated by the random forest model:

Table 24: Feature importance of comfort factors, as predicted by unvalidated random forest model (See appendix E for key to comfort factor names)

Comfort factor	**Feature importance**
co2ppm	0.092546
qa_wt	0.087029
qc_4	0.076873
qc_1	0.067921
qa_age	0.055048
tsa_q3_6	0.047889
qa_ht	0.041067
qc_3	0.035835
rh	0.033643
tsa_q3_7	0.029601
tsa_q3_3	0.028673
q4_8	0.026887

pre_out	0.024042
thist_d0	0.023709
tsa_q3_1	0.022857
eqt_trunk	0.021857
tsa_q3_5	0.021014
tr_ft	0.01858
eqt_feet	0.018072
tsa_q3_4	0.017908
qc_6	0.015795
qc_5	0.014763
eqt_head	0.014604
tr_tr	0.013939
tsa_q3_2	0.01367
ta_ft	0.013306
sound	0.013283
ta_tr	0.013074
va_ft	0.011277
tr_hd	0.010618
va_hd	0.009274
ta_hd	0.008986
q2_2	0.008883
qa_gender_m	0.008512
qc_2	0.008095
va_tr	0.007192
q4_18	0.006303
pre_t	0.005087
lux	0.004721
pre_clo	0.004351
therm_mdl_hd	0.001586
light_yellow	0.000847
scent_Pepper	0.000468
light_blue	0.000319
scent_O&C	0
q2_1_yes	0
therm_mdl_tr	0
therm_mdl_ft	0

7.2.2 Reasons for poor predictive performance of holistic comfort model

The following reasons might account for the poor predictive performance of the holistic comfort models:

1) There seems to be little or no discriminative information in the comfort factors with regards the holistic comfort scores. This may perhaps be due to experimental differences and measurement procedures and instruments, e.g., in lux values, CO_2 concentration, airflow speed, equivalent

temperature. For example, a scatter plot of some of the most important features as estimated by the random forest model shows no discrimination in values between comfortable and uncomfortable:

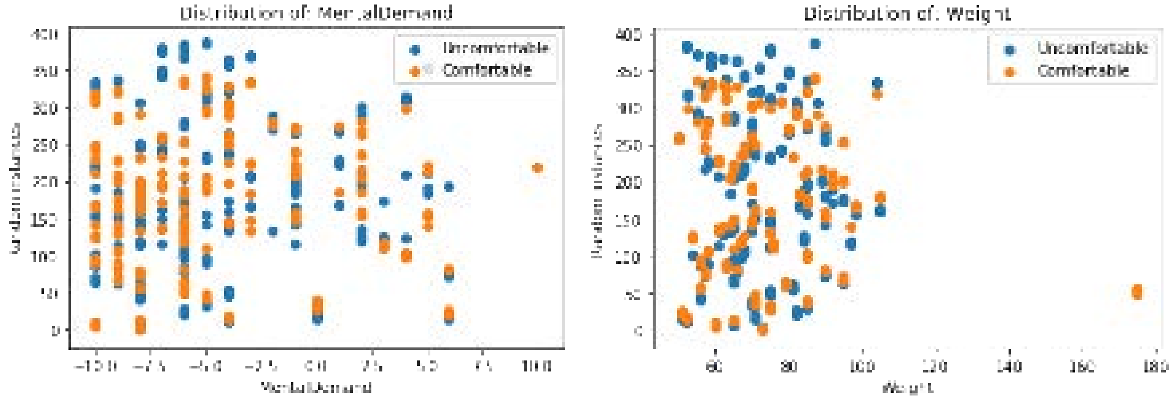


Fig. 52: Scatter plot of most important features as predicted by random forest model, showing no discrimination in comfort

2) The methodology for obtaining the holistic comfort scores might have been sub-optimal.

The holistic comfort sensations were obtained via a magnitude estimation procedure, outlined in Section 5.6. If instead of using the magnitude estimation, we sought to create a model to predict thermal comfort based on a thermal comfort sensation obtained on a well-defined scale, the performance of the machine learning models are shown below:

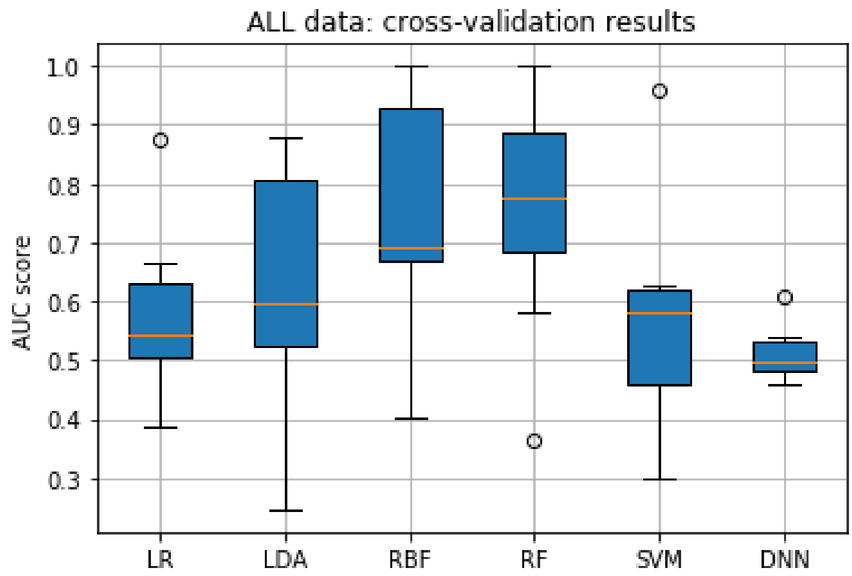


Fig. 53: Cross-validation AUC scores for predicting thermal comfort; mean values are: Logistic regression (LR) = 0.577; Linear discriminant analysis (LDA) = 0.632; Radial basis function network (RBF) = 0.752; Random forest model (RF) = 0.764; Support vector machine with radial basis function kernel (SVM) = 0.565; Deep neural network (DNN) = 0.510

The figure shows a much improved AUC in predicting thermal comfort based on thermal comfort sensation votes on a scale of -3 to 3, as compared to predicting holistic comfort based on magnitude estimation scores as shown in Fig. 50.

7.3 Holistic Comfort Model

Due to the general low predictive performance of the machine learning models, a number of final holistic comfort models are proposed:

1) A radial basis function model based on a limited set of features, achieving an average predictive accuracy of 61%. This model is detailed in Section 7.1.6.

2) A linear discriminant analysis model based on non-validated classification accuracy of 65.7%, as shown in Fig. 51.

In the following, we explain how LDA works.

One way of approaching a classification problem is to assign an item to the category that maximises the posterior probability, as in LDA, Quadratic Discriminant Analysis (QDA) and Naïve Bayes classifiers. In other words, for any set of comfort factors $\boldsymbol{F}$, we define the binary holistic comfort score C_{bin} as follows:

$$C_{bin} = \begin{cases} 0, & \text{if } p(C_{bin} = 0|\boldsymbol{F}) > \ p(C_{bin} = -1|\boldsymbol{F}) \\ -1, & \text{if } p(C_{bin} = 0|\boldsymbol{F}) \leq \ p(C_{bin} = -1|\boldsymbol{F}) \end{cases} \qquad (7.1)$$

That is, we decide that an occupant is comfortable holistically if:

$$\frac{p(C_{bin} = 0|\boldsymbol{F})}{p(C_{bin} = -1|\boldsymbol{F})} > 1 \qquad (7.2)$$

and decide that they are not comfortable if:

$$\frac{p(C_{bin} = 0|\boldsymbol{F})}{p(C_{bin} = -1|\boldsymbol{F})} \leq 1 \qquad (7.3)$$

For the sake of notational convenience, note that the set of factors contained in $\boldsymbol{F}$ includes the equivalent temperature, which is the existing thermal comfort model $\boldsymbol{c}_t$.

This view of the holistic comfort model requires us to model the conditional probabilities $p(C_{bin} = 0|\boldsymbol{F})$ and $p(C_{bin} = -1|\boldsymbol{F})$ which are the probabilities that an occupant is comfortable and uncomfortable respectively, given the set of comfort factors $\boldsymbol{F}$.

However, from Bayes rule, we may rewrite the ratio $p(C_{bin} = 0|\boldsymbol{F})/p(C_{bin} = -1|\boldsymbol{F})$ as:

$$\frac{p(C_{bin} = 0|\boldsymbol{F})}{p(C_{bin} = -1|\boldsymbol{F})} = \frac{p(\boldsymbol{F}|C_{bin} = 0) \times p(C_{bin} = 0)}{p(\boldsymbol{F}|C_{bin} = -1) \times p(C_{bin} = -1)} \qquad (7.4)$$

Therefore, the decision rule can be expressed as follows:

$$\frac{p(\boldsymbol{F}|C_{bin} = 0)}{p(\boldsymbol{F}|C_{bin} = -1)} \gtrless \frac{p(C_{bin} = 0)}{p(C_{bin} = -1)} \qquad (7.5)$$

where $\lambda(\boldsymbol{F})$, the likelihood ratio, and τ, the threshold, often represent the following:

$$\lambda(\boldsymbol{F}) = \frac{p(\boldsymbol{F}|C_{bin} = 0)}{p(\boldsymbol{F}|C_{bin} = -1)}, \qquad \tau = \frac{p(C_{bin} = 0)}{p(C_{bin} = -1)} = \frac{\pi_c}{\pi_u} \qquad (7.6)$$

Thus, one decides that the cabin occupant is comfortable if $\lambda(\boldsymbol{F}) > \tau$, and decides that the occupant is uncomfortable if $\lambda(\boldsymbol{F}) \leq \tau$. Here, π_c and π_u, which are the prior probabilities that an occupant is comfortable and uncomfortable respectively, are often obtained as the relative frequencies of the comfortable and uncomfortable counts respectively in the dataset.

A common assumption is to consider the probabilities $p(\boldsymbol{F}|C_{bin}=0)$ and $p(\boldsymbol{F}|C_{bin}=-1)$ as following multivariate Gaussian distributions, as used in LDA. This assumption often tends to be satisfactory in practice, especially for environmental data such as temperature, humidity, airflow, due mainly to the central limit theorem [Lyon, 2013].

Thus,

$$p(\boldsymbol{F}|C_{bin}=0)=\frac{1}{\sqrt{(2\pi)^d\det\boldsymbol{\Sigma}_C}}\exp\left[-\frac{1}{2}(\boldsymbol{F}-\overline{\boldsymbol{F}}_c)^T\Sigma_C^{-1}(\boldsymbol{F}-\overline{\boldsymbol{F}}_{\boldsymbol{c}})\right] \qquad (7.7)$$

and

$$p(\boldsymbol{F}|C_{bin}=-1)=\frac{1}{\sqrt{(2\pi)^d\det\boldsymbol{\Sigma}_u}}\exp\left[-\frac{1}{2}(\boldsymbol{F}-\overline{\boldsymbol{F}}_u)^T\Sigma_u^{-1}(\boldsymbol{F}-\overline{\boldsymbol{F}}_{\boldsymbol{u}})\right] \qquad (7.8)$$

where

$\overline{\boldsymbol{F}}_c$ is the mean value for all the comfort factors $\boldsymbol{F}$ for test cases where respondents were comfortable holistically,

$\boldsymbol{\Sigma}_C$ is the covariance matrix for all the comfort factors $\boldsymbol{F}$ for for test cases where respondents were comfortable holistically,

$\overline{\boldsymbol{F}}_u$ is the mean value for all the comfort factors $\boldsymbol{F}$ for test cases where respondents were uncomfortable holistically,

$\boldsymbol{\Sigma}_u$ is the covariance matrix for all the comfort factors $\boldsymbol{F}$ for test cases where respondents were uncomfortable holistically, and

d is the number of comfort factors considered, i.e., the length of the vector $\boldsymbol{F}$.

Simplifying the decision rule of Eq. 7.5 by substituting the expressions in (7.7) and (7.8), and taking the natural logarithms yield the following linear decision rule:

$$\boldsymbol{w}^T\boldsymbol{F} \gtrless w_0 \qquad (7.8)$$

where the vector of weights $\boldsymbol{w}$ is given by:

$$\boldsymbol{w}=(\pi_u\boldsymbol{\Sigma}_u-\pi_c\boldsymbol{\Sigma}_c)^{-1}(\overline{\boldsymbol{F}}_c-\overline{\boldsymbol{F}}_u) \qquad (7.9)$$

and the threshold w_0 is given by

$$w_0=\ln\tau+\frac{1}{2}\left(\overline{\boldsymbol{F}}_c{}^T\boldsymbol{\Sigma}_c{}^{-1}\overline{\boldsymbol{F}}_c-\overline{\boldsymbol{F}}_u{}^T\boldsymbol{\Sigma}_u{}^{-1}\overline{\boldsymbol{F}}_u\right) \qquad (7.10)$$

where $\boldsymbol{w}^T\boldsymbol{F}>w_0$

$$C_{bin}=\begin{cases}0, & \text{if } \boldsymbol{w}^T\boldsymbol{F}\geq w_0\\ -1, & \text{if } \boldsymbol{w}^T\boldsymbol{F}<w_0\end{cases} \qquad (7.11)$$

Thus, for any set of comfort factors $\boldsymbol{F}$, increasing any comfort factor f_i would increase the likelihood that $\boldsymbol{w}^T\boldsymbol{F}$ becomes greater than the threshold, and thus push it toward being comfortable, as long as w_i is positive. For a negative w_i, increasing the comfort factor f_i decreases the likelihood that $\boldsymbol{w}^T\boldsymbol{F}$ becomes greater than the threshold, and thus push it toward being uncomfortable. The absolute value of w_i indicates the relative strength of how much the ith comfort factor influences comfort perception.

The weight vector $\boldsymbol{w}$ obtained by training the linear discriminant analysis model is given in Table 25:

Table 25: Weights for linear discriminant analysis (See appendix E for key to comfort factor names))

Comfort factor	Weight	Feature importance
co2ppm	0.14489	0.079908

qa_gender_m	0.21868	0.073579
q2_2	-0.3168	0.058481
qa_wt	-0.3633	0.050642
qa_age	-0.0488	0.04524
lux	0.40672	0.043843
tsa_q3_6	-0.4697	0.041031
qc_3	-0.1378	0.040618
tsa_q3_2	-0.0106	0.039951
pre_clo	0.32086	0.039443
q4_18	0.02295	0.034904
qc_5	-0.1147	0.033825
va_tr	-0.1144	0.032654
tr_ft	-0.3295	0.032123
qc_4	-0.171	0.030612
va_hd	-0.0469	0.02877
pre_t	0.28032	0.027229
rh	0.15078	0.022226
scent_Pepper	0.01346	0.021746
tsa_q3_7	0.09068	0.021287
ta_hd	0.01775	0.018775
pre_out	0.00956	0.018041
thist_d0	-0.258	0.017156
tsa_q3_4	0.23106	0.014284
tsa_q3_5	-0.2623	0.01424
eqt_feet	0.06467	0.012241
light_blue	0.1785	0.011353
ta_ft	0.64176	0.011291
qc_1	-0.3521	0.00914
va_ft	0.0005	0.008052
eqt_trunk	0.07341	0.007951
qc_6	-0.0351	0.007336
eqt_head	0.32621	0.006141
qa_ht	-0.2459	0.006075
q4_8	-0.2717	0.005845
light_yellow	0.05892	0.004644
qc_2	-0.5909	0.004375
therm_mdl_hd	-0.002	0.004011
therm_mdl_tr	0.09118	0.004011
therm_mdl_ft	0.0373	0.004011
scent_O&C	-0.0269	0.003348
tsa_q3_3	-0.1746	0.002858
tr_hd	-0.0493	0.00221
ta_tr	-0.0639	0.001676

tsa_q3_1	-0.0983	0.001323
tr_tr	0.03221	0.001191
q2_1_yes	0.03221	0.000248
sound	0.03221	0.000062

The intercept w_0 is given as $w_0 =$ -0.37961039

Since not all the comfort factors considered in this model may be easily measurable, an alternative model can be created by simply dropping some of the comfort factors during training and testing of the LDA model.

8 Discussion and conclusion (TME/COV)

These results represent the culmination of work by 5 partners in the consortium to form a coherent holistic comfort model (HCM) based on experimental data

The problem of producing a model of holistic comfort is an extremely challenging one. Subjective *thermal* comfort alone is notoriously difficult to assess. *Holistic* comfort has proven even more elusive due to the larger number of factors that can influence it.

The difficulties associated with creating a model are increased by spreading experiments across different partners since the consistency of the experimental protocol turned out to be quite fragile despite much coordination to ensure that the protocol was followed.

Nevertheless, the inclusion of multiple partner results also provides a safeguard against tuning to the characteristics of any one experimental set-up or peculiarities of a particular laboratory or cultural background.

Results for the holistic comfort model not based on an existing thermal model achieves an accuracy of about 61% using a radial basis function network. These results however do not include many thermal factors such as airflow velocity, radiant temperature, clothing level, humidity, etc. With an extended set of comfort factors considered, the validation performance reduces significantly to roughly 53%, which is barely better than random guess, and not significantly better than the existing thermal models; this is due to a reduced set of training examples and increased effects of overfitting due to feature correlations.

However, if we suppose that the environmental parameters such as temperature, humidity, etc., and participant demographic data – such as were investigated in the experimentations –represent the typical range of values that are to be expected in practice when the holistic comfort model is put in use, then we may evaluate the performance of the holistic comfort model by training and testing it on the same dataset, without too much consideration of its generalisation performance. This activity yields an accuracy of about 77% using a random forest model and 66% using linear discriminant analysis, with the mental demand of the task the cabin occupant is engaged in identified as the most important feature by the random forest model. Other factors of high importance identified include: weight, age, temperature sensitivity, the performance of the task the occupant is engaged in and their temperature history. Since the linear discriminant analysis model gives a more explicit mathematical representation as compared to the random forest model, this model is recommended for the holistic comfort model.

In comparison, the traditional baseline models used – Equivalent Temperature, PMV, Adaptive Thermal Model – are only correct at most 53% of the time.

There are several avenues for improvement in the future:

- Further feature engineering might help improve accuracy. Feature engineering is where a set of existing features are combined so that their combined effect is considered by the model. For example, air velocity and air temperature may interact to make the user more or less comfortable in a way that is not a simple linear combination of the two.
- While it was possible to learn features from the data, for example, using deep neural networks (DNNs), DNNs have the drawback that they tend to overfit when the dataset is small.
- In our view, this work should be seen as one that is “in progress” and, like much of scientific knowledge, is subject to review and update.

8.1 Issues to do with experimental protocol

There are clear differences in experimental protocol evident between partners as each partner aimed to meet an array of competing objectives. For example, IKA blindfolded subjects and thus these subjects could not complete parts of the protocol that were visual in nature. They instead reported a 1-10 score for overall holistic comfort rather than drawing a line or giving a number associated with a magnitude estimation. Although this is not wholly incompatible with the verbal subjective qualifier method, it is also not perfectly aligned with it. This misalignment is just one example – there were many individual instances of misalignment over all partners. The misalignment is important because, in all likelihood, it substantially reduced the performance of the resulting model.

Similarly, VIF focused on noise, vibration and harshness (NVH) issues and thus did not record thermal parameters that were part of the base protocol. This difference meant that some important variables could not be included in a model that is based on any aggregated data-set that included VIF.

TME led the deliverable and were the first to produce data but, due to their focus on lighting and scent, they recorded hedonic tone and did not ask respondents to follow the "magnitude estimation" part of the protocol. As with IKA's data, the result is potentially incompatible estimates of subjective comfort.

COV performed their experiments in a car park and made use of prototype airflow sensors. Due to the sensor's prototypical nature, no calibration data was available. Although calibration data was obtained with TMEs help, this calibration data is limited. Thus, the sensor accuracy is somewhat in doubt.

The ambitious nature of the project led the partners to include a multitude of factors and this, in turn, made the experiments long, complicated, and error prone. These additional factors were usually considered fixed or constant for other partners meaning that it is difficult to make use of them when building the model.

The magnitude estimation technique was an unfamiliar method to most experimenters. The idea of the approach is to allow individual subjects to express themselves naturally but also allow for the reports of different subjects to be compared. We noticed that for most experimenters, the subjective estimation of "terrible" corresponded to a short line being drawn and a small numerical value. For VIF, who focused on sound, their subjects gave longer lines for terrible and shorter lines for excellent. Although this is not a problem in itself, it points out the effect that experimenters had on their subjects through whatever briefing was given.

In conclusion, the lack of homogeneity in the data meant that there were very few useful data to train the model, in terms of number of data entries. Since the accuracy of many machine learning algorithms generally increases with increasing amounts of training data, having more homogenous data could improve the performance of the holistic comfort model.

The lack of homogeneity among partner data also implied that the data features (or comfort factors) were mostly noisy, and therefore contained little classification information to correctly discriminate what constitute comfortable from what constitutes uncomfortable. Thus, in order to improve the results, we may in the future explore having all the comfort experiments conducted by one partner who investigates all the priority comfort factors, or perhaps ensure a stricter adherence to the experimental protocol. This would lead to significantly reduced noise (in measurement or procedure) in the comfort factors, leading to improved classification accuracy.

8.2 Key lessons for future work

1. Keep experimental protocols as simple as possible.
2. Pilot any data gathering
3. Gather data in-car, under ordinary use.
4. Align better with ASHRAE approaches to recording subjective comfort.

What is the meaning of this results for the scientific community?

- The results present an advance over the state of the art
- We bring evidence against the intuitive knowledge that holistic and thermal comfort are not the same
- We robustly justify the need for large data-set collection to help identify holistic comfort
- We argue that the vehicle cabin needs to be treated primarily as a human environment where in-use data is likely to be critical to modelling
- We expect that, when published, these results will open the way to further research

Where are we standing now?

- We have a holistic comfort model that can be used by the rest of the project team and that outperforms the baseline model in terms of predicting the holistic comfort, when trained and tested on the same set.
- Additionally, we have a model of thermal comfort that, in addition to the traditional thermal comfort factors, makes use of some non-thermal factors such as light and scent and outperforms the baseline model in terms of predicting subjective thermal comfort.
- More work is needed to further improve the models and ensure that the best performance possible is obtained given the data that has been gathered.
- As we progress to understand what in-car sensors are feasible, further adjustment of the model may be needed in future projects.

Have we filled the gap?

- The project fundamentally calls for a consideration of the comfort environment that goes beyond air temperature. This deliverable meets that need.
- The task description for this part of the project (T1.2) calls for a model that significantly outperforms a baseline comfort model. Although the final model is unable to accurately predict holistic comfort, we were able to outperform the baseline model in terms of predicting thermal comfort. Thus, this deliverable meets that need.
- The remainder of the DOMUS project requires a model that can be efficiently computed and that is based on the most important subset of holistic comfort parameters. This deliverable meets that need.

8.3 Integration of the HCM in the Assessment Framework Implementation Tool (AFIT)

The HCM as presented in this deliverable will be used in WP 2.2 as part of the comfort evaluation step within the virtual assessment of the AFIT. Thereby the HCM will be complemented by the necessary elements to account for situations not covered by the HCM. This complementing module will be described in detail in D2.3

9 Recommendations

The key results and achievements include:

1. The DOMUS consortium collected and summarised experimental datasets from each of the 5 involved partners, involving a total of 149 participants over an elapsed duration of 242 hours.
2. We produced comparative results for a series of models and a variety of sub-selections of the experimental datasets. The full aggregated dataset produces a binary comfort classifier with Logistic Regression that is accurate 78% of the time.
3. In comparison, the baseline thermal comfort model was only able to correctly predict comfort 58% of the time for the same dataset.
4. This deliverable provides the model parameters and associated equations for the best performing model.

These results meet the requirements set out in the objectives for this part of the project and provide a strong foundation for the remainder of the DOMUS work to build upon.

Our recommendations are as follows:

1. The model should be currently adopted in DOMUS in such a way that allows for an updated model to be provided in the near future.
2. Additional work is needed to further test and validate the model. For example, it should be possible to achieve a better than chance (>50%) accuracy when applying a predictive model derived from 4 partners to data obtained by the 5^{th}.
3. Further improvements to the model may be possible by, for example, using other machine learning techniques, feature engineering and systematic data alignment. This aspect should continue to be explored in parallel with other work that makes use of the model.

10 Risk register

Risk No.	What is the risk	Probability of risk occurrence[1]	Effect of risk[2]	Solutions to overcome the risk
#1	An incorrect model is adopted by DOMUS leading to incorrect estimation of holistic comfort in other parts of the project	2	1	Further validation of the model; continued development of model and replacement of the model as improvements are found; clear identification of limitations of model
#2	Source data is incorrectly collected leading to an incorrect model	1	1	Continued checking of source data by each partner to ensure that it is of the highest quality.

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Project partners:

#	Partner	Partner Full Name
1	IDIADA	IDIADA AUTOMOTIVE TECHNOLOGY SA
2	CRF	CENTRO RICERCHE FIAT SCPA
3	TME	TOYOTA MOTOR EUROPE
4	Volvo Cars	VOLVO PERSONVAGNAR AB
5	AGC	AGC GLASS EUROPE SA
6	DNTS	DENSO Thermal Systems S.p.A.
7	Faurecia	Faurecia Sièges d'Automobile
8	HUTCH	HUTCHINSON SA
9	IEE	IEE International Electronics & Engineering S.A.
10	LIST	LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY
11	COV	COVENTRY UNIVERSITY
12	Fraunhofer	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.
13	IKA	RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN
14	TECNALIA	FUNDACION TECNALIA RESEARCH & INNOVATION
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13 Appendix A – Quality Assurance

The following questions should be answered by all reviewers (WP Leader, peer reviewer 1, peer reviewer 2 and the technical coordinator) as part of the Quality Assurance Procedure. Questions answered with NO should be motivated. The author will then make an updated version of the Deliverable. When all reviewers have answered all questions with YES, only then the Deliverable can be submitted to the EC.
NOTE: For public documents this Quality Assurance part will be removed before publication.

Question	WP Leader / Peer reviewer 1	Technical Coordinator / Peer reviewer 2
	James Brusey (COV)	IDIADA
Do you accept this deliverable as it is?	Yes, although there might be additional changes to the HCM in order to make it functional to the AFIT and the Control logic. If these changes take place, they will be reflected in up-coming deliverables of WP 2	Yes, although there might be additional changes to the HCM in order to make it functional to the AFIT and the Control logic. If these changes take place, they will be reflected in up-coming deliverables of WP 2
Is the deliverable completely ready (or are any changes required)?	Yes	Yes
Does this deliverable correspond to the DoW?	Yes	Yes
Is the Deliverable in line with the DOMUS objectives?	Yes	Yes
WP Objectives?	Yes	Yes
Task Objectives?	Yes	Yes
Is the technical quality sufficient?	Yes	Yes

14 Appendix B – Questionnaire A

- **PERSONAL CHARACTERISTICS**

1.1 Age	1.2 Gender	1.3 Mother tongue	1.4 Height	1.5 Weight
			cm	kg

- **TEMPERATURE/ACTIVITY HISTORY**

2.1. Have you been exercising (e.g. running, cycling, swimming) during the last 30 minutes?

Yes
No

2.2. Have you been outside during the last 30 minutes?

Yes
No

If **yes**, how low? __________min

2.3. Is your area of residence less than 50km away from [experimentation location]?

Yes
No

If **no**, what is your area of residence? _______________________________

2.4. Have you been traveling outside of your area of residence & the area of [experimentation location] during the past week? (e.g. different country, different geographical region)

Yes
No

If **yes**, please fill the first row of the table below.
In order to have understand your temperature history we would need to know the places you have been during the last week (just area/region, no exact location needed).

	Yesterday (D-1)	D-2	D-3	D-4
Location				

	D-5	D-6	1 week ago (D-7)
Location			

- **TEMPERATURE SENSITIVITY ASSESSMENT**

This survey is about your preference, sensitivity and reaction to heat and cold, as people differ in all these aspects.
For each question, choose the option that best reflects your own preference, sensitivity and reaction to heat and cold, in comparison to others.

*3.1. Generally speaking, what kind of temperatures **do you prefer**?*

I prefer colder temperatures						I prefer warmer temperatures
1	2	3	4	5	6	7

3.2. *People differ in how **quickly** or intensely they **experience warmth**. Indicate how quickly you experience warmth.*

Compared to others, I experience **heat sitting still** (at a computer, watching TV, reading a book):

Much later	Later	A bit later	Like everyone else	A bit quicker	Quickly	Much quicker

3.3. *People differ in how **quickly** or intensely they **experience cold**. Indicate how quickly you experience cold.*

Compared to others, I experience **cold sitting still** (at a computer, watching TV, reading a book):

Much later	Later	A bit later	Like everyone else	A bit quicker	Quickly	Much quicker

3.4. *People differ in how **quickly** or intensely they **react to a warm environment**. Indicate how quickly or intensely you experience the following situation.*

Compared to others, a warm environment gives me a warm body:

Much later	Later	A bit later	Like everyone else	A bit quicker	Quickly	Much quicker

3.5. *People differ in how **quickly** or intensely they **react to a cold environment**. Indicate how quickly or intensely you experience the following situation.*

Compared to others, a cold environment gives me a cold body:

Much later	Later	A bit later	Like everyone else	A bit quicker	Quickly	Much quicker

3.6. *People differ in how **quickly** or intensely they **respond to sitting still for a long time**. Indicate how quickly or intensely you experience the following situation.*

Compared to others, **sitting still** for a long time makes me **feel cold**:

Much later	Later	A bit later	Like everyone else	A bit quicker	Quickly	Much quicker

3.7. *People differ in how quickly or intensely they* ***respond to physical exertion****. Indicate how quickly or intensely you experience the following situation.*

Compared to others, **physical exertion** gives me a **warm body**:

Much later	Later	A bit later	Like everyone else	A bit quicker	Quickly	Much quicker

- **NOISE SENSITIVITY ASSESSMENT**

Below are a number of statements addressing individual reactions to noise. After reading each statement, please tick the box that represents your level of agreement with the statement.

	Strongly disagree				Strongly agree
4.1. I wouldn't mind living on a noisy street if the apartment I had was nice.					
4.2. I am more aware of noise than I used to be. *					
4.3. No one should mind much if someone turns up his or her stereo full blast once in a while.					
4.4. At movies, whispering and crinkling candy wrappers disturb me. *					
4.5. I am easily awakened by noise. *					
4.6. If it's noisy where I'm studying, I try to close the door or window or move someplace else. *					
4.7. I get annoyed when my neighbors are noisy. *					
4.8. I get used to most noises without much difficulty.					
4.9. It would matter to me if an apartment I was interested in renting were located across from a fire station.					
4.10. Sometimes noises get on my nerves and get me irritated. *					
4.11. Even music I normally like will bother me if I'm trying to concentrate. *					
4.12. It wouldn't bother me to hear the sounds of everyday living from neighbors (footsteps, running water, etc.).					
4.13. When I want to be alone, it disturbs me to hear outside noises. *					
4.14. I'm good at concentrating no matter what is going on around me.					
4.15. In a library, I don't mind if people carry on a conversation if they do it quietly.					
4.16. There are often times when I want complete silence. *					
4.17. Motorcycles ought to be required to have bigger mufflers. *					
4.18. I find it hard to relax in a place that's noisy. *					
4.19. I get mad at people who make noise that keeps me from falling asleep or getting work done.*					
4.20. I wouldn't mind living in an apartment with thin walls.					
4.21. I am sensitive to noise. *					

15 Appendix C – Questionnaire B

- **THERMAL COMFORT**

General
Please rate on these scales how you feel NOW.

	Cold *-3*	Cool *-2*	Slightly cool *-1*	Neutral *0*	Slightly warm *+1*	Warm *+2*	Hot *+3*
Overall							
Head							
Trunk - Front							
Trunk - Rear							
Feet							

Stickiness
Please rate on these scales how you feel NOW.

	Not sticky *0*	Slightly sticky *+1*	Sticky *+2*	Very sticky *+3*
Overall				
Head				
Trunk - Front				
Trunk - Rear				
Feet				

- **TIME TO DISCOMFORT**

Imagine experiencing the situation you just experienced it in a real vehicle and not in an artificial environment.
Considering elements such as seating, temperature, sounds, lighting, and odours, how many minutes do you think it would take you until experiencing the ride as uncomfortable?

_________ minutes

- **MULTISENSORY COMFORT**

How comfortable did you find the following elements during the simulation?

- Thermal environment
- Acoustic environment
- Seating
- Visual environment
- Olfactory environment
- Overall situation

On the **following page**

- Please draw a straight line. The line can be as long, as you prefer.
- Please write a positive number as an answer.

Thermal environment

Acoustic environment

Seating

Visual environment

Olfactory environment

Overall situation

16 Appendix D – Questionnaire C

- **TASK EVALUATION**

Please mark the vertical line that best indicates your experience of the task. Please respond spontaneously without thinking too much about the answer: there is no right or wrong answer.

Mental Demand
How much mental and perceptual activity was required (eg., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex?

Very low Very high

Physical Demand
How Much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was The task easy or demanding, Slow or brisk, slack or strenuous, Restful or laborious?

Very low Very high

Temporal Demand
How much Time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was The pace slow and leisurely or rapid and frantic?

Very low Very high

Performance
How Successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How Satisfied were you with your performance in accomplishing these goals?

Very good Very poor

Effort
How Hard did you have to work (mentally and physically) to accomplish your level of performance?

low high

Frustration
How insecure, discouraged, irritated, stressed and annoyed versus secure. gratified, content, relaxed and complacent did you feel during the task?

Very low Very high

17 Appendix E

pre_out - outside temperature (degree Celsius)
pre_t - temperature between questionnaires (degree Celsius)
pre_clo - clothing insulation (clo)
qa_age - age of cabin occupant
qa_ht - height of cabin occupant (cm)
qa_wt - weight of cabin occupant (kg)
q2_1 - binary variable indicating whether or not occupant has been outside for the past 30 minutes
q2_2 - exposure time (minutes)
thist_d0 - temperature on day of experiment (degree Celsius)
tsa_q3_1 - temperature sensitivity assessment Q3.1 (See appendix B of D1.3)
tsa_q3_2 - temperature sensitivity assessment Q3.2 (See appendix B of D1.3)
tsa_q3_3 - temperature sensitivity assessment Q3.3 (See appendix B of D1.3)
tsa_q3_4 - temperature sensitivity assessment Q3.4 (See appendix B of D1.3)
tsa_q3_5 - temperature sensitivity assessment Q3.5 (See appendix B of D1.3)
tsa_q3_6 - temperature sensitivity assessment Q3.6 (See appendix B of D1.3)
tsa_q3_7 - temperature sensitivity assessment Q3.7 (See appendix B of D1.3)
q4_8 - noise sensitivity assessment Q4.8 (See appendix B of D1.3)
q4_18 - noise sensitivity assessment Q4.18 (See appendix B of D1.3)
ta_hd - air temperature at head (degree Celsius)
ta_tr - air temperature at trunk (degree Celsius)
ta_ft - air temeperature at feet (degree Celsius)
tr_hd - radiant temperature at head (degree Celsius)
tr_tr - radiant temperature at trunk (degree Celsius)
tr_ft - radiant temeperature at feet (degree Celsius)
va_hd - air velocity at head (m/s)
va_tr - air velocity at trunk (m/s)
va_ft - air velocity at feet (m/s)
rh - relative humidity (m/s)
co2ppm - carbon dioxide concentration (ppm)
lux - illuminance (lux)
sound - sound level (dBi)
qc_1 - driving activity load index - mental demand (See appendux D of D1.3)
qc_2 - driving activity load index - physical demand (See appendux D of D1.3)
qc_3 - driving activity load index - temporal demand (See appendux D of D1.3)
qc_4 - driving activity load index - performance (See appendux D of D1.3)
qc_5 - driving activity load index - effort (See appendux D of D1.3)
qc_6 - driving activity load index - frustration (See appendux D of D1.3)
qa_gender_m - binary variable indicating gender (1 for Male, 0 otherwise)
light_blue - binary variable indicating whether ambient light is blue (1 for Blue, 0 otherwise)
light_yellow - binary variable indicating whether ambient light is yellow (1 for Yellow, 0 otherwise)
scent_O&C - binary variable indicating whether scent is Orange and Cinammon (1 for O&C, 0 otherwise)
scent_O&C - binary variable indicating whether scent is Orange and Cinammon (1 for O&C, 0 otherwise)
scent_Pepper - binary variable indicating whether scent is Peppermint (1 for Peppermint, 0 otherwise)
eqt_head - equivalent temperature at head (degree Celsius)
eqt_trunk - equivalent temperature at trunk (degree Celsius)
eqt_feet - equivalent temperature at feet (degree Celsius)