

## Roads Toward Comfort Improvement For Future Mobility

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# Roads Toward Comfort Improvement For Future Mobility

Gerbera Vledder



# **Roads toward comfort improvement for future mobility**

## **Dissertation**

for the purpose of obtaining the degree of doctor

at Delft University of Technology

by the authority of the Rector Magnificus, prof.dr.ir. T.H.J.J. van der Hagen,

chair of the Board for Doctorates,

to be defended publicly on

Wednesday 26 November 2025 at 12:30 o'clock

by

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born in Kempton Park, South Africa

This dissertation has been approved by the promotor.

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## Summary

Mobility plays a vital role in connecting people and businesses. As sustainability and technological advancements reshape the mobility landscape, there is a growing demand for future-proof solutions. This dissertation explores passenger comfort as a key factor in the adoption of emerging mobility modes, including turboprop aircraft, sleeper trains, and automated vehicles (AVs). Although these modes offer environmental and operational benefits, their success hinges on passenger acceptance, with comfort being a central determinant.

The primary aim of this dissertation is to deepen our understanding of the factors that influence (dis)comfort and to propose design interventions that enhance passenger comfort in future mobility contexts. These (dis)comfort experiences are shaped over time by interactions between the individual, the environment, the product, and the task at hand. To meet the primary aim of this dissertation, the thesis is structured in three chapters: Chapter 2 examines the environment, Chapter 3 focuses on the person, and Chapter 4 addresses the product and user task, each providing a distinct lens on comfort and discomfort in future mobility.

First, the environmental factors in the context of sustainable mobility are considered (chapter 2). Section 2.1 investigates (dis)comfort factors in turboprop aircraft through two studies. In the first study, 33 participants experienced a simulated flight; in the second, 97 participants took part in a real ATR 72 flight; both flights lasted 70 minutes. Noise, vibration, and the seat were identified as the main discomfort factors, while space, lighting, temperature, and the seat were most important for comfort. Notably, the ranking of these factors differs from studies on jet engine aircraft, where anthropometry is more prominent. This highlights how (dis)comfort experiences are shaped by the specific travel context.

Section 2.2 defined the physical space and environment requirements for comfortable sleep while travelling. The sleeping postures of 189 participants in which they usually fall asleep and the sleeping posture in which they spend most time were recorded. Participants also reported factors that hinder sleep in cars, trains, and airplanes. Findings showed that a bed size of 200 by 90 cm accommodates all participants, although a smaller size of 171 by 76 cm may suffice for one-night travel, as many individuals prefer side sleeping with bent legs. Darkness, silence, and temperature control were found to be essential for comfortable sleep in transit environments.

Chapter 3 shifts the focus to the 'person' dimension in comfort research. In section 3.1, data from 249 participants were used to examine the accuracy of self-reported body mass and stature. On average, stature was overreported by 1.31 cm, while body mass was underreported by 1.45 kg, especially among individuals with a body mass index over 25. Two models were developed to correct self-reported data, providing researchers with tools to adjust for inaccuracies in ergonomic and comfort studies where measured data are unavailable.

To study the relationship between upright sleeping postures, movements, and comfort (section 3.2), 16 participants completed six 90-minute naps in a lab, in a seat with five different backrest angles and one flat bed. Posture observations combined with (dis)comfort questions showed that comfort increased, discomfort decreased, and posture variety reduced when participants slept in a more reclined seat. Most participants slept with a straight back against the backrest and with straight legs, except on the flat bed. Upright angles evoke discomfort-triggered movements, especially in the head and leg area, while reclined angles allow greater torso mobility, enabling more 'natural' flat sleeping behaviour and improved comfort.

Continuing this line of inquiry, section 3.3 investigates the human spinal curve in two reclined seating configurations with backrest angles of 140° and 115°. Thirty-six participants were measured, and a statistical shape model of the back contour was developed. The model revealed a need for adjustable lumbar support and highlighted the potential of incorporating a second pivot joint, next to the backrest recline, to better accommodate neck curvatures.

Chapter 4 addresses product and task-specific comfort. Given the strong impact of interior noise identified in Chapter 2, section 4.1 evaluates the effectiveness of active noise-cancelling headphones (ANC) and earplugs. In a grounded fuselage, 24 participants experienced four different acoustic environments: jet sound, turboprop sound, turboprop sound with ANC headphones, and turboprop sound with earplugs. Comfort was measured using questionnaires, including a developed Ear Local Discomfort questionnaire. Results confirmed the effectiveness of both ANC headphones and earplugs in improving comfort and suggested that such solutions could make propeller aircraft more attractive than jet aircraft.

In section 4.2, 24 participants evaluated 12 night train interiors and four day train interiors in a virtual reality environment. The study aimed to explore the influence of privacy and security on comfort and to identify differences between day and night travel needs. Findings revealed that privacy, noise isolation, visual

overview, and social control were key to comfort in night train environments. During daytime travel, privacy, spaciousness, visual overview, and opportunities for interaction were most important. Additionally, security was rated slightly more important by women during night train journeys.

Chapter 5 concludes the dissertation with a general discussion. The central research question: *'How can the passenger (dis)comfort experience be improved in future mobility solutions?'*, is addressed across multiple contexts. In turboprop aircraft, noise emerges as an important discomfort factor. Solutions such as earplugs and noise-cancelling headphones are shown to be effective, and further innovation may include integrating noise cancellation into the aircraft seat. In automated vehicles, where passengers are expected to engage in activities such as sleeping, this dissertation provides advice on optimal backrest angles as well as a spinal curve model to support the activity based on an understanding of sleeping postures and sleep movement. It also outlines key environmental comfort needs in sleeper trains, trains, and cars, including noise management, motion mitigation, temperature control, privacy, and safety.

This dissertation provides a foundation for comfort research and offers design practical guidelines for enhancing comfort in future mobility modes. Further research should focus on validating these findings in real-world transportation scenarios and include a more diverse user population. Further considerations may involve examining cultural differences in sleep behaviour, car passenger safety in non-traditional postures, and the adoption of emerging mobility solutions.

## Samenvatting

Mobiliteit speelt een cruciale rol in de verbinding van mensen en bedrijven. Nu duurzaamheid en technologische ontwikkelingen het mobiliteitslandschap veranderen, groeit de vraag naar toekomstbestendige oplossingen. Deze dissertatie onderzoekt passagierscomfort als een sleutelfactor in de acceptatie van toekomstige vormen van transport, waaronder turbopropvliegtuigen, nachttreinen en geautomatiseerde voertuigen (AV's). Hoewel deze vervoersmiddelen milieu- en operationele voordelen bieden, is hun succes afhankelijk van de acceptatie door passagiers, waarbij comfort een centrale rol speelt.

Het hoofddoel van deze dissertatie is om meer inzicht te krijgen in de factoren die (dis)comfort beïnvloeden en om ontwerpinterventies voor te stellen die passagierscomfort in de toekomst verbeterd. Deze (dis)comfortervaringen worden over tijd gevormd door interacties tussen het individu, de omgeving, het product en de uit te voeren taak. Om dit doel te bereiken, is de dissertatie opgebouwd in drie hoofdstukken: Hoofdstuk 2 onderzoekt de omgeving, Hoofdstuk 3 richt zich op de persoon, en Hoofdstuk 4 behandelt het product en de gebruikstaak. Elk hoofdstuk biedt een andere blik op comfort en discomfort in toekomstige mobiliteit.

Eerst worden de omgevingsfactoren in het kader van duurzame mobiliteit besproken (Hoofdstuk 2). In sectie 2.1 wordt (dis)comfort in turbopropvliegtuigen onderzocht via twee studies. In de eerste studie ondergingen 33 deelnemers een gesimuleerde vlucht; in de tweede namen 97 deelnemers deel aan een echte ATR 72-vlucht, beide vluchten duurden 70 minuten. Geluid, trillingen en de stoel werden als belangrijkste discomfortfactoren geïdentificeerd, terwijl ruimte, verlichting, temperatuur en de stoel het meest bijdroegen aan comfort. Opvallend is dat deze rangorde verschilt van studies naar straalvliegtuigen, waar lichaamsafmetingen een grotere rol spelen. Dit benadrukt dat (dis)comfort wordt beïnvloed door de specifieke context van de reis.

In sectie 2.2 worden eisen voor de fysieke ruimte- en omgeving gedefinieerd voor comfortabel slapen tijdens het reizen. De slaaphoudingen waarin 189 deelnemers doorgaans in slaap vallen, en de houdingen waarin zij de meeste tijd doorbrengen, werden vastgelegd. Daarnaast gaven deelnemers aan welke factoren hun slaap belemmeren in auto's, treinen en vliegtuigen. Uit de resultaten bleek dat een bed van 200 bij 90 cm voldoende is voor alle deelnemers, al kan een kleiner formaat van 171 bij 76 cm al volstaan voor een enkele overnachting, aangezien veel mensen het liefst op hun zij slapen met opgetrokken benen. Licht

en geluidsintensiteit en temperatuurregeling bleken essentieel voor comfortabel slapen tijdens vervoer.

Hoofdstuk 3 richt zich op de 'persoon' binnen comfortonderzoek. In sectie 3.1 werd de nauwkeurigheid van zelf gerapporteerde lichaamslengte en gewicht onderzocht met gegevens van 249 deelnemers. Gemiddeld overschatte deelnemers hun lengte met 1,31 cm. Gewicht werd met 1,45 kg onderschat, vooral bij mensen met een BMI boven de 25. Twee modellen werden ontwikkeld om zelf gerapporteerde data te corrigeren, waarmee onderzoekers data in ergonomisch en comfortonderzoek kunnen aanpassen wanneer gemeten data afwezig is.

Om de relatie tussen rechtop slapen, beweging en comfort te bestuderen (sectie 3.2), deden 16 deelnemers zes dutjes van 90 minuten in een laboratorium, zittend op een stoel met vijf mogelijke rugleuninghoeken en één vlak bed. Houding observaties, samen met (dis)comfortvragen, toonden aan dat comfort toenam, discomfort afnam en houdingvariatie afnam bij vlakkere rugleuning. De meeste deelnemers sliepen met een rechte rug tegen de rugleuning en met gestrekte benen, behalve op het vlakke bed. In rechtop zittende houdingen veroorzaakt discomfort meer beweging, vooral in hoofd- en beengedeelte, terwijl vlakkere hoeken meer rompmobiliteit toelaten, wat een natuurlijke slaaphouding en comfort bevordert.

Voortbouwend op de vorige sectie, onderzoekt sectie 3.3 de curve van de wervelkolom van deelnemers zittend in twee rugleuninghoeken van 140° en 115°. Zesendertig deelnemers werden gemeten en een statistisch model van de rug contour werd ontwikkeld. Het model toonde de noodzaak van een verstelbare lendensteun en suggereerde het potentieel van een tweede scharnierpunt, naast de rugleuning hoek, om de nekkromming beter te ondersteunen.

Hoofdstuk 4 behandelt comfort gerelateerd aan het product en de taak. Gezien de vastgestelde sterke invloed van geluid op comfort in Hoofdstuk 2, evalueert sectie 4.1 de effectiviteit van active noise cancelling koptelefoons (ANC) en oordoppen. In een geaarde vliegtuigromp, ervaarden 24 deelnemers het geluid van vier vliegtuig interieurs: straalmotor, turboprop, turboprop met ANC-koptelefoon en turboprop met oordoppen. Comfort werd gemeten met vragenlijsten, waaronder een speciaal ontwikkelde lokale oor discomfort vragenlijst. Deze studie bevestigde dat ANC-koptelefoons en oordoppen het comfort verbeteren en dat dergelijke oplossingen helpen turbopropvliegtuigen aantrekkelijker te maken dan straalvliegtuigen.

In sectie 4.2 beoordeelden 24 deelnemers 12 nacht en vier dag trein interieurs in een virtual reality-omgeving. Het doel was om de invloed van privacy en veiligheid op comfort te onderzoeken en verschillen tussen dag- en nachtreizen te identificeren. De resultaten toonden aan dat privacy, geluidsisolatie, visueel overzicht en sociale controle essentieel zijn voor comfort in nachttreinen. Tijdens dagreizen waren privacy, ruimtelijkheid, visueel overzicht en mogelijkheden voor interactie het belangrijkste. Daarnaast werd veiligheid als iets belangrijker beoordeeld door vrouwen tijdens nachttreinreizen.

Hoofdstuk 5 sluit de dissertatie af met een algemene discussie. De centrale onderzoeksvraag: "Hoe kan de (dis)comfortervaring van passagiers worden verbeterd in toekomstige mobiliteitsoplossingen?" wordt beantwoord in verschillende contexten. In turbopropvliegtuigen blijkt geluid een belangrijke bron van discomfort. Oplossingen zoals oordoppen en ANC-koptelefoons zijn effectief, en verdere innovatie zou zich kunnen richten op geluidsreductie in de vliegtuigstoel. Voor zelfrijdende voertuigen biedt deze dissertatie advies over optimale rugleuningshoeken en een rugcontourmodel ter ondersteuning van de slaapactiviteit, gebaseerd op inzicht in slaaphoudingen en slaapbewegingen. Daarnaast worden belangrijke omgevingsfactoren voor comfort besproken in dag/nacht treinen en auto's, waaronder geluidsbeheersing, bewegingsregulatie, temperatuurregeling, privacy en veiligheid.

Deze dissertatie biedt een basis voor comfortonderzoek en levert praktische ontwerpaanbevelingen voor het verbeteren van comfort in toekomstige mobiliteitsvormen. Vervolgonderzoek zou zich moeten richten op het valideren van deze bevindingen in realistische vervoerssituaties en het betrekken van een diversere gebruikersgroep. Verder onderzoek zou culturele verschillen in slaapgewoonten, veiligheid van autodeelnemers in niet-traditionele houdingen, en de acceptatie van opkomende mobiliteitsoplossingen kunnen verkennen.

## Reading Guide and Glossary

|            |   |
|------------|---|
| ANC        | Active Noise Cancellation   |
| AV         | Automated Vehicle   |
| BMI        | Body Mass Index   |
| BRA        | Backrest Roll Angle   |
| B-Spline   | A B-spline is a smooth curve defined by control points and piecewise polynomials  |
| ComfDemo   | Comfort in the cabin Demonstrator, a Horizon 2020 funded European project   |
| COVID-19   | A highly contagious respiratory illness caused by the SARS-CoV-2 virus, first identified in 2019, which led to a global pandemic                      |
| dB(A)      | Unit of sound that measures sound intensity using an A-weighted filter  |
| DINED      | Anthropometric data in design by Delft University of Technology   |
| DTA        | Discomfort Triggered Adjustments  |
| ECG        | Electrocardiogram   |
| EDA        | Electrodermal Activity  |
| ELD        | Ear Local Discomfort  |
| Flying V   | An aircraft constructed in the shape of a V   |
| HREC       | Human Research Ethical Committee  |
| HRV        | Heart Rate Variability  |
| IDE        | Industrial Design Engineering, a faculty at the Delft University of Technology  |
| IFE        | In-Flight Entertainment   |
| Jerk       | The rate of change in acceleration over time  |
| KQ         | Key Question  |
| KSS        | Karolinska Sleepiness Scale   |
| Kyphometer | An instrument used to measure the curvature of the spine in two dimensions  |
| LAeq       | The average A-weighted noise level over a specified time period   |
| Laterally  | Side sleeping, in the sleeping posture context. When the spine is aligned parallel to the bed surface and the sagittal plane is oriented horizontally |
| LPD        | Local Postural Discomfort   |
| NDRA       | Non-Driving Related Activities  |
| nREM       | The non-Rapid Eye Movement sleep stage is the initial phase of the sleep cycle  |
| P5/P95     | Percentile of a certain population  |
| PC         | Principal Component   |
| PCA        | Principal Component Analysis  |

|           |  |
|-----------|--|
| Pitch     | The distance between a point on one seat and the same point on the seat in front, indicating legroom space   |
| PSG       | Polysomnography  |
| PSQI      | Pittsburg Sleep Quality Index  |
| PVT       | Psychomotor Vigilance Test   |
| Python    | Programming language   |
| rMEQ      | reduced Morningness-Eveningness Questionnaire  |
| RMSE      | Root Mean Square Error   |
| SBA       | Seat Back Angle  |
| SD/STD    | Standard Deviation   |
| SPA       | Seat Pan Angle   |
| SPFS      | Samn-Perelli 7-point Fatigue Scale   |
| SPL       | Sound Pressure Level   |
| SPSS      | A software program used for statistical analysis in research   |
| SSM       | Statistical Shape Model  |
| Supine    | Sleeping on the back, in the sleeping posture context. When the face and torso are facing upward and the spine is in a neutral alignment along the bed surface |
| TIB       | Time In Bed  |
| Turboprop | An airplane that has turbo propeller engines instead of jet engines.   |
| TWA       | Time Weighted Average  |
| WBV       | Whole Body Vibration   |

CHAPTER



# INTRODUCTION

## 1.1. Making the mobility sector future-ready

*“As the backbone that connects European citizens and business, mobility matters to us all. We have no time to lose in getting it fit for the future”* according to European Commissioner for Transport Adina Vălean (European Commission, n.d.). In a globalized world, mobility is needed to transport people for business meetings, holidays, or family visits. However, this mobility needs to be made future-proof. Many transport possibilities are available, but in light of climate change, some of these do not yet meet the requirements. In 2020, trucks and passenger cars were responsible for two-thirds of the global CO<sub>2</sub> emissions from transport (Ritchie, 2020). The aviation sector is responsible for 2.5% of the global CO<sub>2</sub> emissions in 2023 (Lombardo & Gauch, 2025), and is one of the fastest-growing polluters with a CO<sub>2</sub> increase of 2.5 times from 2000 to 2019 (Ritchie, 2020). In Europe it is expected that the number of flights will be back to the level of 2019 (before COVID-19) in 2025 and will have an expected average annual flight growth of 2% (*EUROCONTROL Forecast Update 2024-2030*, 2024). This shows a need to switch to sustainable transport options in the future, which has led to a revival of the European night train network (**Fig. 1.1a**) and the use of turbo propeller airplanes (**Fig. 1.1b**). Also, the development of airplanes with alternative CO<sub>2</sub> neutral propulsion systems is ongoing (Ansell & Haran, 2020). And for the automotive sector, the switch to electric vehicles falls within this need for CO<sub>2</sub> neutral transport as electric cars tend to have a lower carbon footprint than petrol or diesel cars over their lifetime (Ritchie, 2024). Another future trend is the development of automated vehicles (AVs) (**Fig. 1.1c**), which can increase road safety and enhance drivers’ freedom of activity. It is expected that by 2030, 12% of new passenger cars will have level 3+ automated technologies included (Deichmann et al., 2023). Automated vehicles create opportunities for enhanced driver support, ultimately, fully automated driving. The adoption of future transport modes (night trains, turboprop airplanes, AVs) depends on various factors from the passenger’s perspective, where comfort is a critical one. This dissertation explores how these modes can be made more attractive by prioritizing passenger comfort.

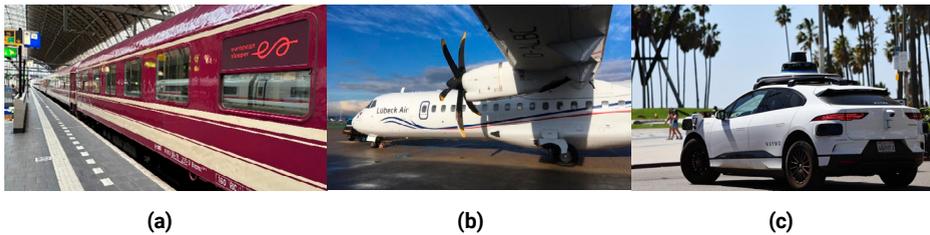


Figure 1.1 a: European sleeper night train service going from Brussels to Venice in 2025 (European Sleeper, n.d.), b: The ATR 72 propeller aircraft, c: Waymo a level 4 autonomous vehicle (Crothers, 2024).

## 1.2. Comfort and Discomfort

Alongside travel cost and travel time, comfort level is an important factor in the passengers' mode choice on long-distance rail transport (Heufke Kantelaar et al., 2022). Vink et al. also underpinned the relevance of travel efficiency (point-to-point) and comfort in the choice among train, turboprop, or jet-engine airplanes (Vink et al., 2022). This shows the relevance of comfort as one of the factors defining the willingness to use a specific transport mode and shows that comfort can give an important competitive advantage. For that reason, the scientific knowledge on comfort is explored. The definition of comfort and discomfort that is used within this thesis is: "comfort is seen as a pleasant state or relaxed feeling of a human being in reaction to its environment" where "discomfort is seen as an unpleasant state of the human body in reaction to its physical environment" (Vink & Hallbeck, 2012). Comfort and discomfort are part of the human experience. People can experience comfort and discomfort at the same time; they are not direct opposites. **Figure 1.2** shows the hypothetical relation between discomfort and comfort as presented by Zhang et al. (1996). The absence of discomfort will not necessarily result in comfort or vice versa. Discomfort is more associated with physical factors (fatigue, posture, restlessness, pain, and strain), while comfort is more associated with psychological factors (luxury, relaxation, or a sense of being refreshed)(Zhang et al., 1996).

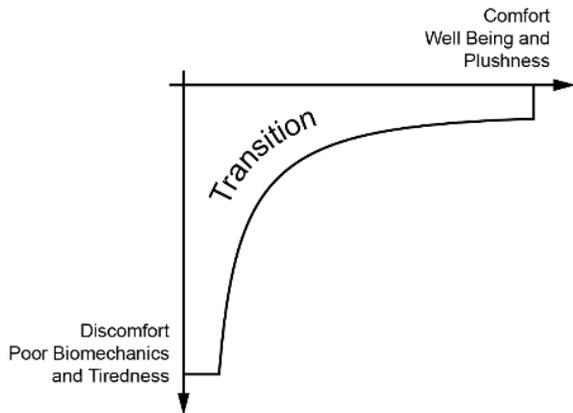


Figure 1.2 Relationship of discomfort and comfort (Zhang et al., 1996).

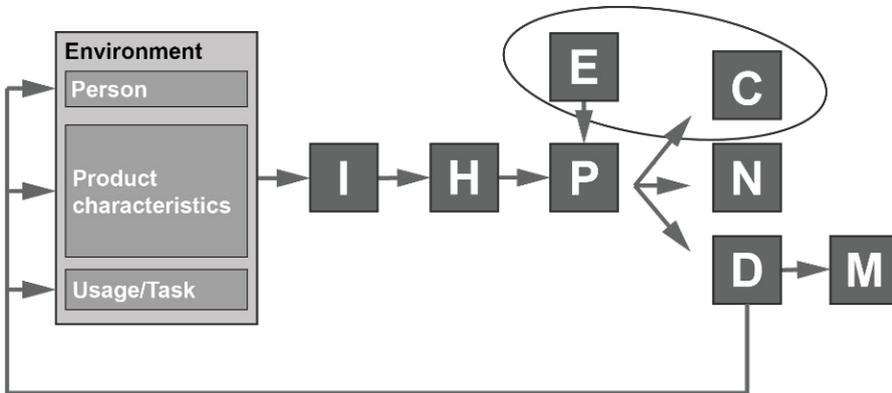


Figure 1.3 Comfort model as proposed by Vink & Hallbeck (2012).

Vink & Hallbeck (2012) created a framework to understand how comfort and discomfort are formed (**Fig. 1.3**), combining the models from De Looze et al. (2003) and Moes (2005). The person, the product, and the task are located in a certain environment, and these all influence the interaction (I) and cause human body effects (H) (such as tactile sensations, body posture change, or muscle activation). The perceived effects (P) are influenced by these human body effects, but also by the expectations (E) the person has about the situation. The perceived effects can create comfort (C), might not be noticed (nothing (N)), or might lead to discomfort (D). These factors (environment, person, product, and task) differ for each context and how they relate might be different as well. Naddeo et al. (2014) updated the Vink & Hallbeck model by defining the perceivable effects (P) to be postural, physiological, cognitive, and environmental. Which can be used for testing and evaluating the comfort perception and human response.

Additionally, Naddeo et al. (2014) introduce the concept of a primary element (directly contributes to the formation of a comfort/discomfort perception, e.g., anthropometric measurements) and modifier elements (modifying a previously formed perception, e.g., time of sitting). The temporal effect was further proved by Mansfield et al. (2014), who showed the effect of vibration on the formation of discomfort, and a negative effect of time on discomfort (fatigue). Additionally, Mansfield et al. (2014) indicated an interaction effect between these two factors, leading to an acceleration of discomfort development.

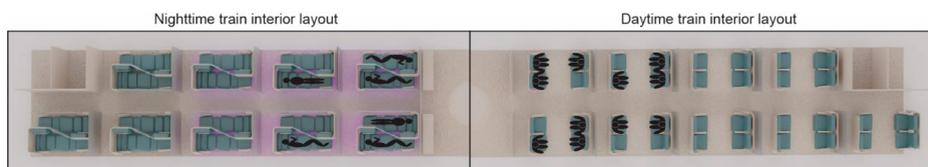
Many studies consider comfort in mobility. For instance, Bouwens et al. (2018) looked at comfort-influencing factors in an airplane. For sleeping in an aircraft the factors influencing comfort are: Light, smell, vibrations, noise, temperature, and anthropometry. For Watching in-flight entertainment (IFE), these factors are the same, but smell, vibrations, and temperature turned out to be more important, while for sleeping the most important factors influencing comfort are: light, smell, and vibrations. This does not mean that if the lighting or smell in an aircraft is perfect, everything else is not important while watching IFE. According to the 'cake model' by Mansfield et al. (2020) all factors influencing comfort need to reach at least the minimum level of performance, for the entire experience to be acceptable.

### 1.3. Future-ready travel options

Replacing the jet engine aircraft on short-haul European trips, the turbo propeller (turboprop) aircraft is a possible alternative. This aircraft in its current design already uses 10-60% less emissions on short-haul trips compared to jet-engines (Babikian et al., 2002). Due to their high efficiency, propeller-driven aircraft are also expected to feature prominently in many future electric airplane designs (Schäfer et al., 2018). However, there is good reason to believe that acoustic comfort needs extra attention if propeller turboprop aircraft are to replace the current jet-engine aircraft. Turboprop aircraft and other propeller-driven aircraft are usually 10 to 30 decibels louder on the inside (Kincaid et al., 1997), and they have higher noise and vibration levels in the interior compared to jet-engine aircraft (Mansfield et al., 2021).

Once, sleeper trains were seen as an adventurous and comfortable way of travel around Europe, but with the rise of cheap flights, they disappeared largely from our minds as a way of travel (Martin, 2017). In recent years, European sleeper train routes have been making a comeback. As a climate-friendly travel option, sleeper trains show great potential. Sleeper trains could be a good alternative for replacing airplane trips that are between 1500-2000km (Goeverden et al., 2019). But their interiors look outdated and have not evolved with our current needs for

privacy, security, and comfort (Railway pro, 2024). One of the sleeper train's main selling points might be that you have the possibility of a full night's rest, arriving at inner-city stations, and eliminating the need for an overnight stay at a hotel. This is especially challenging in seated carriages, as most passengers prefer to sleep on a flat surface. There are also business concerns making the offering of a night train a difficult business case. Night trains have a higher operating cost per passenger, a higher space per passenger, lower utilization of vehicles (only at night), and higher operating costs result from night operations (Davies Gleave et al., 2017). Making it relevant to look into novel train concepts, for example, the option to make the interior of the train changeable by passengers from day to night train, as proposed in the master thesis of Out (Out, 2024)(**Fig. 1.4**).



**Figure 1.4** Train interior adjustable by passengers themselves from day to night layout (Out, 2024).

Automated driving has become more realistic in the past decade. Options now range from driver assistance (e.g., lane correction) to fully automated vehicles (AVs). It is expected that in 2050, 50% of all vehicle travel will consist of AVs (Papaioannou et al., 2025), in some places level four vehicles are already driving around (Bhuiyan, 2023). The potential of AVs include higher road safety, better allocation of road capacity, and a chance to turn the drivers' time into productive time in the form of sleeping. Before the large-scale implementation of AVs some challenges need to be tackled, but what we do know is that if AVs reach higher levels of automation, drivers will change to passengers and they will have more time for non-driving related activities (NDRAs), including sleep (Cai et al., 2024; Wilson et al., 2022). Therefore, the need for guidelines on how to facilitate comfortable sleep during an AV trip has increased.

## 1.4. Knowledge gap

Comfort and discomfort can be determined and influenced by many factors, of which many have been researched, but as the context and transport mode change, so do these influencing factors. It is impossible to study all changes and effects on comfort. In this PhD thesis, a selection is made as some changes have a good chance of happening: propeller airplanes might be used more often, sleeper trains might become more important, and automated driving will be introduced with NDRAs like sleeping. Some of these options are new or re-

discovered, there might be factors that need to be added or whose importance needs to be reconsidered.

For instance, in turboprop airplanes, the factors influencing comfort might be fairly similar to those in jet-engine airplanes, but some might become more important or less important. Sound pressure levels in a turboprop can range from 83 dB(A) to 92 dB(A) (Zevitas et al., 2018), which can be compared to standing next to a vacuum cleaner (80 dB) or a pneumatic hammer (90 dB) (Parnell & Wassermann, 2014). The impact of noise on passenger comfort in a turboprop should first be investigated, and after this, solutions should be explored to make this more sustainable aircraft competitive in terms of acoustic comfort.

The introduction of AVs and the rediscovery of the night train creates the opportunity for sleeping during travel. Although sleep has been studied before from a medical or neurologic perspective, in the field of ergonomics and comfort, sleep research is a novel field (Smulders, 2024, p. 24). Especially if we look at upright sleeping. Comfortably sleeping in transit shows great opportunities for reducing the experienced length of travel time (Molin et al., 2020), and willingness to travel by night trains (Heufke Kantelaar et al., 2022), but generally sleeping is not always considered as the most comfortable activity. In an aircraft sleeping is considered to be the least comfortable activity (Bouwens et al., 2017). From the literature, it is not clear how people (the 'person') move and which postures they take during the (upright) sleeping activity, how the sleeping activity is influenced by the (upright) sleeping posture, the mobility environment, and how the seat influences sleep, all in the area of sleeping comfort. Therefore, in this PhD thesis also comfort in different upright sleeping positions is researched.

You could say that the 'person' is at the core of comfort and discomfort research, as a seat can never be comfortable by itself; the person decides if a seat is comfortable or not (Mansfield et al., 2020). Because 'the person' is important, it is especially important to have adequate tools for testing comfort in humans and to include the right user group. In comfort research, we often need to have information on the participants' stature and body mass. In some studies the body mass or stature is determined by interviews, and in some it is measured, but it is not known what the difference is between self-reported stature and body mass versus the measured stature and body mass of the participant. This can lead to a mismatch in participant selection, difficulties in comparing studies, and it can lead to errors in studies where it is not possible to measure participants during a test. Concerning the 'person', it is also relevant to know the human back contour, since the human contour can be used to optimize the seat contour, and improve comfort (Franz et al., 2011). Previous studies have mainly focused on the back contour in an upright 'driver' sitting posture. This leaves a knowledge

gap concerning the back contour in other sitting activities, such as relaxing or sleeping and the transition from one position to the other. Therefore, this PhD will also explore the back contour of people in an upright sitting and relaxed reclined backrest angle.

## **1.5. Research aim**

This dissertation aims to create new knowledge regarding (dis)comfort factors that influence the experience of passengers in future mobility solutions, and on how this (dis)comfort experience can be improved. This background information can be helpful in creating tools for industry, which can be used to balance comfort needs with for instance economic or technical requirements. Additionally, this dissertation aims to increase the academic knowledge in these fields. This leads to the following main research question:

### **How can the passenger (dis)comfort experience be improved in future mobility solutions?**

It is impossible to study all possible mobility situations. A selection of mobility situations has been made. As was described before the assumption is that more propeller airplanes will be introduced. Therefore, the propeller aircraft is studied. Another assumption is that people will sleep in future AVs, trains, and aircraft. Additionally, because of limited space in most vehicles, sleeping might be done while sitting upright. In the upright sleeping position, the human sleeping posture, the backrest angle, and back contour should be taken into account, which is studied as well. The sleeper train might be a good alternative to short-haul flying. That is why the sleeper train is included in this PhD thesis.

Throughout the dissertation, the following key questions will be treated within the different mobility contexts:

1. What are the comfort factors that need to be improved (what is the problem)?
2. What are the solutions that could be explored to improve these comfort factors in the selected mobility solutions?

## **1.6. Embedding in the IDE Faculty**

This dissertation is embedded within the research vision and strategic direction of the Faculty of Industrial Design Engineering (IDE) at TU Delft, where human-centered, interdisciplinary design research is at the core. The IDE faculty aims to develop knowledge, methods, and tools that improve the quality of life through

meaningful innovation, an ambition that aligns strongly with the goals of this research on comfort in future mobility.

First, the thesis is grounded in the faculty's core strength: **designing for human experience**, and slogan **design for our future**. The exploration of (dis)comfort during travel, particularly in the transport modes of tomorrow, such as automated vehicles, turboprop aircraft, and sleeper trains, reflects IDE's commitment to understanding human needs in real-world contexts. The research takes a holistic approach that spans environmental conditions, product characteristics, human anthropometry, and user behaviour, demonstrating the faculty's integrative approach in practice.

Second, the work connects directly to the faculty research themes:

- It contributes to the **Mobility** of people, a key research focus at IDE, by addressing the design of future transport experiences in a sustainable and user-centred manner.
- It can contribute to the **Health** theme, for instance, through the study of sleep and its interaction with physical support systems and noise exposure, highlighting how design can promote well-being during transit.
- Through empirical studies and novel tools (e.g., upright sleep posture classification, discomfort maps), the thesis also strengthens the **AI & Data-Informed Design** initiative by providing valuable data, promoting further development of computational methods for personalized and adaptive comfort design.

Importantly, the outcomes of this PhD also support the faculty's ambition to create **design knowledge with societal impact**. By offering evidence-based guidelines for sleeping in transit, acoustic comfort, and posture support, the dissertation provides actionable knowledge for industry partners developing the next generation of vehicle interiors. These insights can inform not only physical design decisions but also policy-level discussions on inclusive, accessible, and sustainable transport.

## 1.7. Dissertation outline

Each chapter of this dissertation will focus on a different comfort factor based on the comfort model as described by Vink & Hallbeck (2012), in this way answering the key research questions. **Figure 1.5** visually shows the dissertation structure. The included articles in this dissertation are divided among the chapters to create a clear structure, but it is relevant to mention that although some included articles are categorized under a single chapter, they might deal with multiple

comfort factors, as in reality a product is always used in an environment and by a person, and it is difficult to solely look into a single aspect without discussing the context.

Chapter 1 places the thesis within a broad context, describing the research’s background and framework.

Chapter 2 discusses environmental comfort factors that influence the (dis) comfort experience in the turbo propeller aircraft, and sleep in vehicles and trains.

Chapter 3 includes fundamental work on tools for ergonomic research (evaluating research participants), the upright sleeping posture and movement frequency, and the human back contour in different backrest angles, with the person as the central topic.

Chapter 4 explores (dis)comfort for specific products and activities, such as the use of noise-cancelling headphones in a turbo propeller aircraft. Additionally, the influence of interior elements in a sleeper train on the privacy, security, and comfort experience is explored.

Chapter 5 presents a discussion and conclusion, reflecting on the overall work presented in this dissertation, the main research question, and gives recommendations for further research.

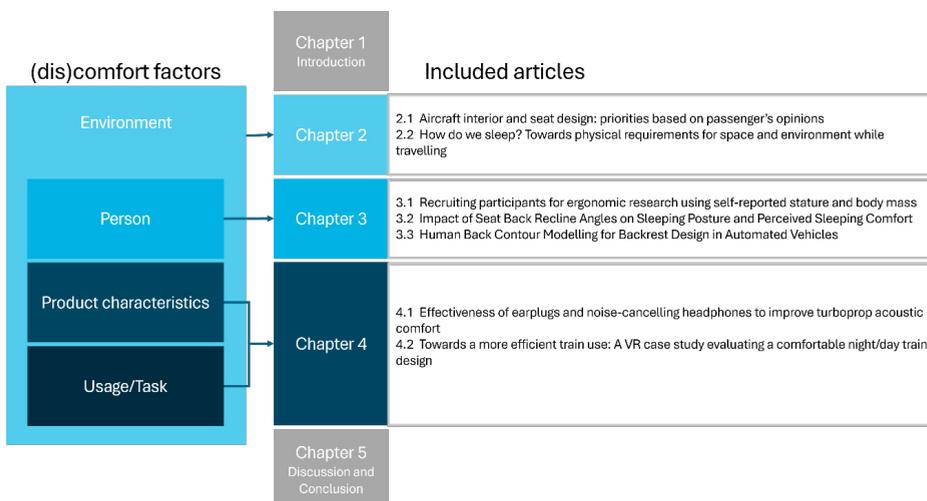


Figure 1.5 Dissertation structure

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CHAPTER



# ENVIRONMENT

In the introduction (section 1.2, Fig. 1.3), it is explained that comfort or discomfort arises from variables related to the environment, the person, the product, and the task. The following chapter will focus on environmental factors influencing comfort and discomfort. As future transport modes evolve, the context changes, necessitating updated requirements regarding the environment to arrive at a comfortable experience. This chapter will define relevant environment factors influencing comfort and discomfort in future transportation modes and compare these with the current situation.

In section 2.1, interior variables influencing comfort and discomfort in a turboprop airplane are defined and compared to those in a jet-engine airplane, highlighting differences in the importance of variables between the two types of aircraft. The research includes two test flights in an ATR72 turboprop aircraft with a total of 96 passengers. In section 2.2, the environmental and product preferences for napping in a 'general' vehicle are explored by asking people to take a short nap during the day.

This chapter is based on the following articles:

1. Vink, P., Vledder, G., Song, Y., Herbig, B., Reichherzer, A. S., & Mansfield, N. (2022). Aircraft interior and seat design: priorities based on passengers' opinions. *International Journal of Aviation, Aeronautics, and Aerospace*, 9(1). <https://doi.org/10.15394/ijaaa.2022.1679>
2. Vink, P., Vledder, G., Smulders, M., & Song, Y. (2025). How do we sleep? Towards physical requirements for space and environment while travelling. *Applied Ergonomics*, 122. <https://doi.org/10.1016/j.apergo.2024.104386>

## **2.1. Aircraft interior and seat design: priorities based on passengers' opinions**

### **Abstract**

Comfort is an important factor for passengers in the selection of airlines, and electric propeller aircraft will be an important element of future sustainable aviation. In this paper, we studied the order of importance of different (dis) comfort factors regarding traveling with propeller aircraft. Two experiments were conducted, one was a simulation flight on the ground with 33 participants and the other were two real flights with 97 participants. All participants were asked to rank the importance of different (dis)comfort factors in different phases of flights. Results indicated that though there are differences between the simulation and the real flights, noise, vibration and the seat are among the most important factors regarding discomfort, and space, lighting, temperature and seat are the most important factors of comfort. The results are different to those reported from previous studies on travelling by jet, where anthropometry is the most important factor. This finding suggests a difference in passenger perception between travelling by propeller propulsion and jet engines, and casts new requirements on the aircraft interior and service design for future sustainable aviation.

## Introduction

For many years, comfort has been an important factor for passengers in choosing the airline and the aircraft (Brauer, 2006) and it makes sense to design a comfortable interior and seat to attract passengers. It might not only be important to feel comfortable during the flight but also feeling comfortable about the flight (Vink, 2020). Decision influencing factors in the future of mobility might incorporate new elements such as sustainability, and future travel may have a requirement to use more sustainable solutions. Many sustainable aircraft concepts use some form of propeller drive in the engine (IATA, 2019). In more sustainable travel options, the same comfort rules might apply to customer satisfaction. Therefore, it is important to study the relevant comfort factors for usage of more sustainable turboprop and electric propeller airplanes.

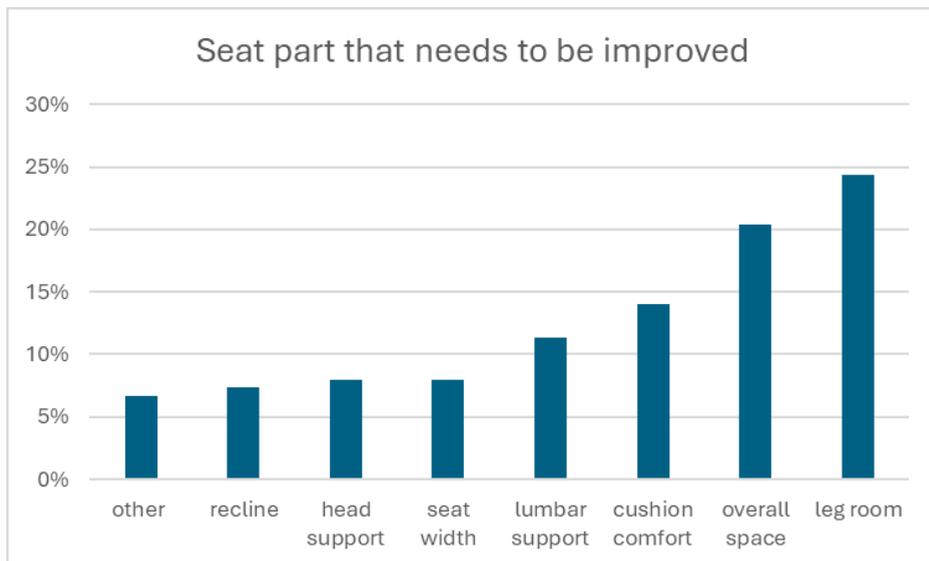
According to Krist (1993) and Bubb et al. (2015), comfort is established by six factors: anthropometry, climate, sound, vibrations, illumination and smell. Bouwens et al. (2018) showed that among 183 passengers, 'anthropometry' was the most important factor influencing comfort, meaning that the legroom and seat width are insufficient for the size of different human body parts. The second most important factor was 'noise,' which is mainly the sound that the engines and aerodynamics produce. However, the sound of a crying baby and fellow passengers can be annoying as well (Lewis et al., 2016). The third factor was temperature, which could be too low or high. It could also be local temperature that is annoying, like cold feet or a draft in the neck. Smell, illumination, and vibration were mentioned as fourth, fifth, and sixth factors. It is interesting to see that the importance of the factor is dependent on the activity of the passengers (Bouwens et al., 2016); for example, the third most important factor while sleeping was 'temperature' and while watching in-flight entertainment (IFE) it was light. Some studies also mention the "proximity of others" as the overall most important factor for comfort (e.g., Lewis et al., 2017), but many mention physical space (e.g., Vink et al., 2012).

As anthropometrics is often the most important factor, it might be good to look more in detail which seat element needs attention. In Table 2.1.1, the opinion of 246 passengers on several seat elements is shown (Bouwens, 2018). It is probably no surprise that leg room is mentioned as number one, e.g., Vink et al. (2012) reported the same result. The bottom cushion, which is number two, also needs attention. Asking the same group what needs to be improved, resulted again in legroom as number one, and overall space and cushion as number two and three (see Figure 2.1.1).

Table 2.1.1. Importance of different airplane seat features for perceived comfort according to 246 passengers (Bouwens, 2018). 1=most important/11= least important.

|                      |
|----------------------|
| 1. leg room          |
| 2. bottom cushion    |
| 3. foot space        |
| 4. seat width        |
| 5. head support      |
| 6. lumbar support    |
| 7. Recline           |
| 8. Armrest           |
| 9. head side support |
| 10. tray table       |
| 11. foot rest*       |

*\*for Asian travellers foot rests are more important and comes just after head side support.*



**Figure 2.1.1. Percentage of the 246 passengers that states that this part of the seat needs to be improved.**

Sustainability seems to become more important for aircrafts. Electric propeller aircrafts are in development aiming at closer to zero emission, and several have already been flown as demonstrators. This process is already on its way as current cargo turboprops will be changed to use hydrogen fuel using conversion kits (Mandel, 2021), which includes a fuel cell and an electric powertrain to replace conventional turboprop engines. Thus, there might be more electric

propeller driven airplanes coming. However, a serious issue for the adoption of the turboprop aircraft is the comfort experience of the passenger, primarily because the noise and vibration inside a turboprop cabin (Mansfield et al., 2021) might play a larger role in the overall comfort experience.

For instance, the noise levels in the cabins of turboprop aircraft are typically 10 to 30 decibels louder than commercial jet noise levels (Kincaid et al., 1997). For a turboprop the noise is derived from a combination of the engine power source and noise arising from the passage of blades past the wing. To study the priorities of passengers in the factors influencing comfort data two experiments were completed in which the sound of propellers was apparent. The question in this analysis is: is the order of importance of different comfort factors as contributors to aircraft interior comfort experienced different in propeller aircrafts in comparison to known data of jet aircrafts?

## Method

Two experiments were carried out. In one experiment, 33 participants (average age 24.5 years (19-37); length 1.751 m (1.60-1.92)) sat in a Boeing 737 interior in six rows. Five rows were occupied by 30 participants (3x3 next to each other in 31" pitch). In the front row, three participants were located on one side and had more legroom. The Boeing 737 stayed on the ground and a flight of 70 minutes was simulated. A speaker simulating a turboprop flight was located just behind the passengers, a screen in the front of the cabin showed a video of the flight. Passengers had to complete several questionnaires and did not leave their seat. After 35 minutes, a drink was served. Three times during the "flight" (during ascent, cruise, and descent) the question was asked "please mark the three factors most contributing to your experienced level of discomfort: temperature, noise, lighting, air quality, vibration, seat and space". To apply the results in the CLEAN SKY 2 ComfDemo project temperature and air quality are separated in this study. In the study of Bouwens et al. (2018) climate was defined as one element. Norrefeldt et al., 2021 also measured humidity, carbon dioxide (CO<sub>2</sub>), Total Volatile Organic Compounds, and temperature and studied comfort regarding air quality separately from comfort regarding temperature. The same question was asked for comfort three times. Per factor, the percentage of persons mentioning the factor was calculated. A Cochran Q test for repeated measures with binary outcomes ( $p < .05$ ) was used to see if the factor differed from the other sample points in the simulated flight (across all measurement points and in direct comparisons of t1 vs t2, t2 vs t3, and t1 vs. t3).



**Figure 2.1.2.** Participants on their way to the test flight in an ATR72.

The second experiment was a flight of 70 minutes in an ATR72 turboprop with 30 minutes at a cruising altitude of 17,000 feet (see Figure 2.1.2). The seats were 2x2 (so no middle seat) with 35" pitch, creating more legroom than usually experienced in regional flights. The aircraft had passenger capacity of 60; experimenters also travelled on the flights. Two flights with 52 and 45 passengers respectively were completed. After the flight, the passengers were asked the same question: "please mark the three factors most contributing to your experienced level of discomfort: temperature, noise, lighting, air quality, vibration, seat and space". Again, the same question was asked for comfort. Per factor, the percentage of individuals mentioning the factor was calculated.

## Results

In the first experiment, there was no significant difference between the three recorded comfort/discomfort scores. So, during the simulated flight no significant changes were observed. The percentage of participants mentioning the factors influencing discomfort over all three recordings is shown in Figure 2.1.3. Noise in this case is the most dominant factor, followed by seat and space.

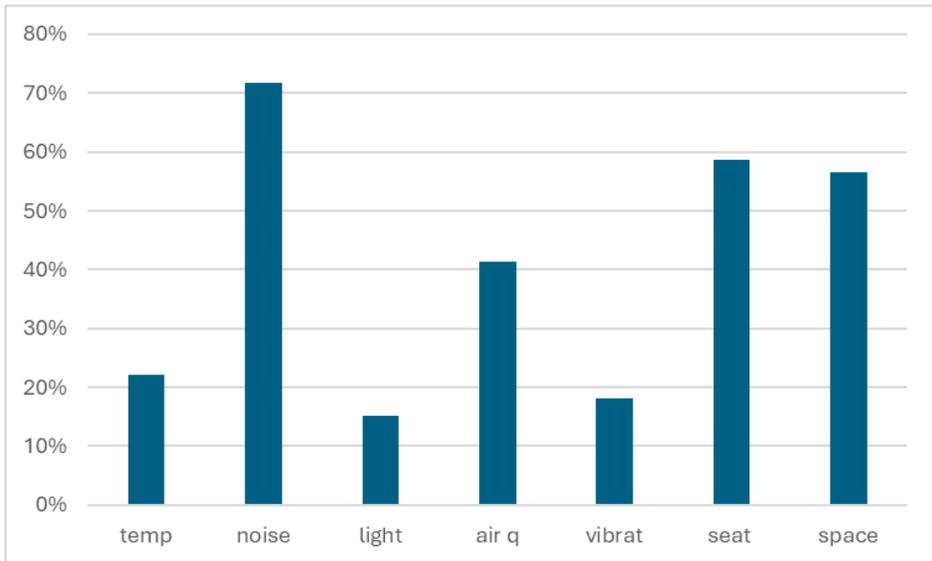


Figure 2.1.3. The percentage of the 33 passengers mentioning the factor related to discomfort averaged over the three times that it was sampled in the test in the 737 cabin (air q=air quality).

The factor influencing comfort that was most mentioned was temperature (see figure 2.1.4), followed by light and seat.

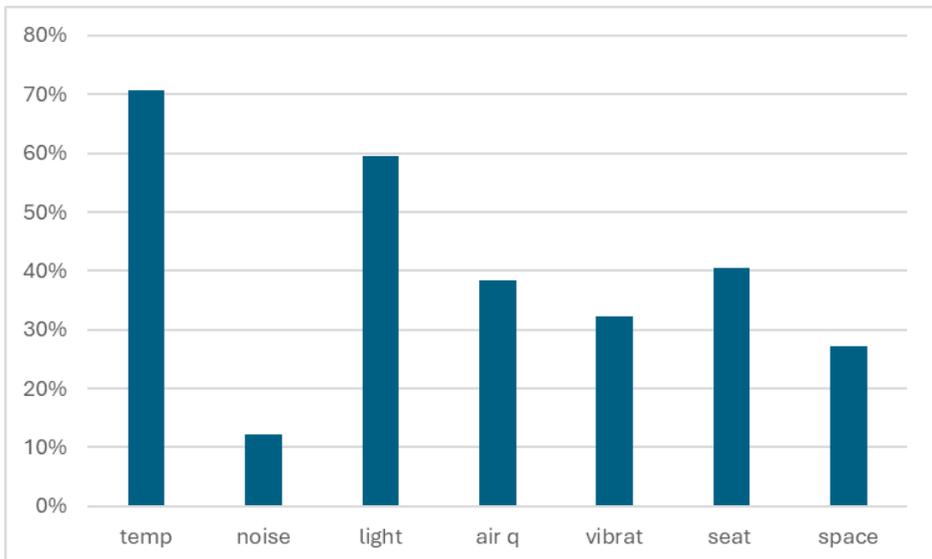


Figure 2.1.4. The percentage of the 33 passengers mentioning the factor related to comfort averaged over the three moments it was recorded (air q=air quality).

In the second experiment 94 participants ((35 females, 49 males, average age 33.86 (SD 14.31). average length 1,755 m (SD 0,102), average BMI 23.60 (SD 3.24) completed the questionnaire (a further 5 were incomplete and excluded from the analysis). Again, noise was the dominant factor influencing discomfort (see Figure 2.1.5), followed by seat and vibration. For comfort space followed by lighting and temperature were the factors mentioned mostly related to comfort as Figure 2.1.6.

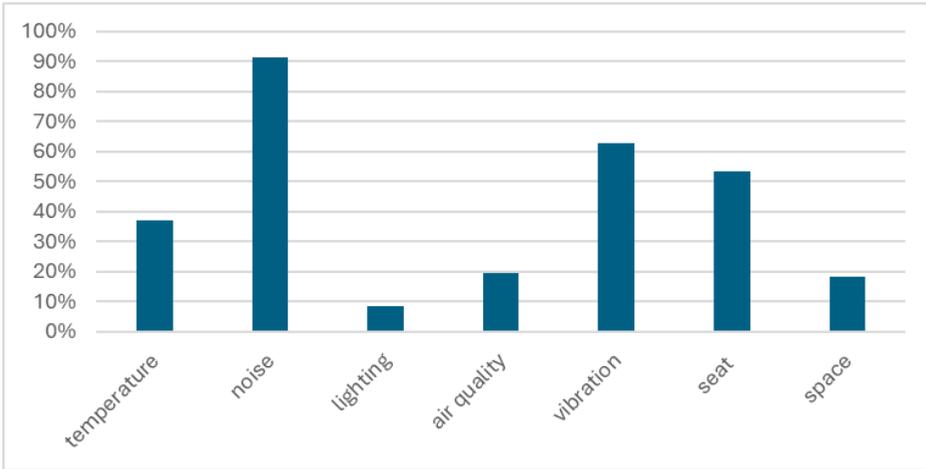


Figure 2.1.5. Percentage of the 94 passengers that report this factor influencing discomfort after the flight.

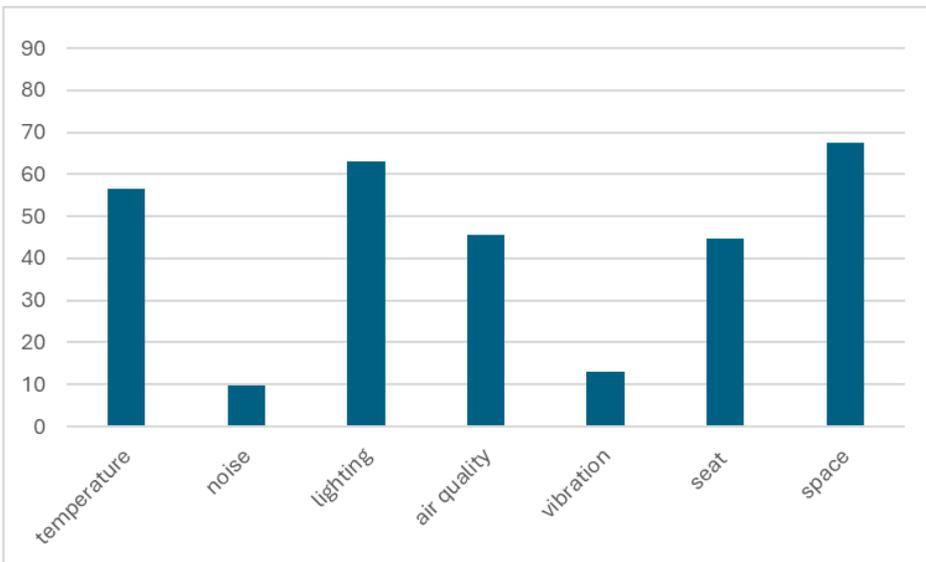


Figure 2.1.6. Percentage of the 94 passengers that report this factor influencing comfort after the flight.

## Discussion

### Anthropometry

In current jet aircrafts anthropometry (the fit between human and seat) is the main point related to comfort according to Bouwens et al. (2018), while in our research the seat was number two regarding discomfort and three or four regarding comfort. Bouwens et al. (2018) used a different approach and studied airplanes in general. As most airplanes are jets, turboprops did not get much attention in their study. In their approach passengers had to choose between two factors and select the most important one. Based on that way of studying the factor most mentioned was anthropometry. In our study, comfort and discomfort were separated. First the question on discomfort was asked and passengers could mention the most 'annoying' factor first and then participants could mention the factor contributing to comfort. The anthropometrics having most influence in jet airplanes is also confirmed in other studies (e.g. Vink et al., 2012; Kremser et al., 2012). Also, in the propeller driven airplane the seat is very important as it is the second most important factor related to discomfort and the third related to comfort. Within the seat, the legroom and cushion need attention, as they are the two with most importance of different airplane seat features for perceived comfort according to 246 passengers (Bouwens, 2018). Hinninghofen and Enck (2006) also identified that seat comfort is associated with seat pitch, seat width, legroom and quality of upholstery.

Kuo and Jou (2017) described that seat pitch and seat width are primary factors for passengers to upgrade to the premium economy class based on their previous experience. Anjani et al. (2021) found that comfort increases when the pitch gets larger. In figure 2.1.7 a pitch of 28" with a seat width of 17" is related to a very low comfort (score 4), while a pitch of 30" with a seat width of 17" gives a just acceptable comfort score of 6. Widening the seat has a large effect. At a seat, pitch of 30" an 18" seat width gives a significantly better score than a 30" pitch and 17" wide seat and it is better than a 32" pitch with a 17" wide seat. Differences in pitch size can explain the difference in importance of the seat 'factor' on comfort and discomfort in the second test compared to previous research. The pitch in the second test was relatively large (35"), which might influence the priorities as well. It is unknown whether passengers contribute the larger pitch to the seat or space. The relatively large pitch could have increased the feeling of "spaciousness" and/or the 'anthropometry and these two are related.

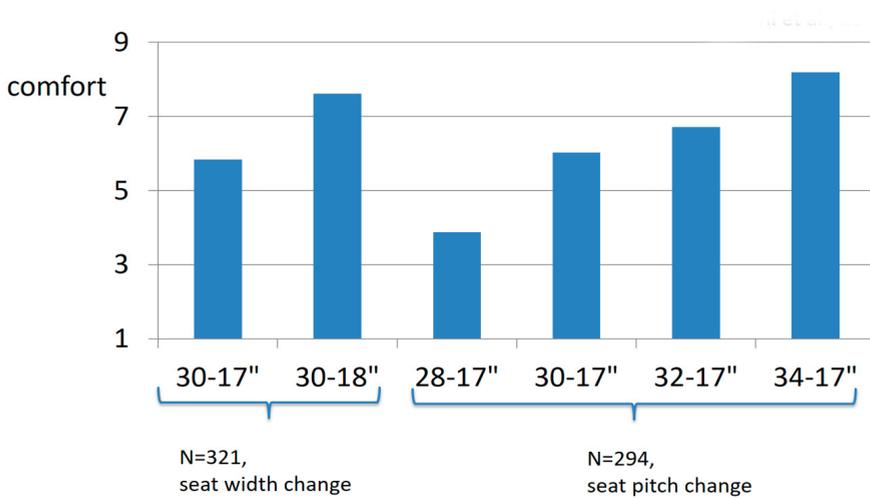


Figure. 2.1.7. Comfort score on a scale from 0-10 (10=extreme comfort) for different pitches and seat widths (Source: Anjani et al., 2021).

### Noise

It seems that in turboprops the noise is the factor that needs most attention. This is in line with other studies on turboprop airplanes (e.g. Mansfield et al., 2021; Vink et al., in press). Cabin noise can increase the awareness of symptoms such as swollen feet and headache (Mellert et al., 2008), but can also cause differences in comfort experience and mood (Pennig et al., 2012). Therefore, for future propeller aircrafts it might be wise to look at noise reduction systems. Already in 1997, Kincaid et al. (1997) stated that noise levels in the cabins of turboprop aircraft are louder than commercial jet noise levels. The turboprop noise spectrum is dominated by multiple harmonically related tones. Active structural acoustic control and engine synchronisation is a method to reduce noise, but also other systems like noise dampening material and noise cancelling headphones might be helpful. Mechanical options might be: changing the frequency of the harmonics by changing the propeller (e.g., by the number of blades) or change the propeller position such that there is less aerodynamic interaction with the rest of the airframe.

### Vibration

Vibration is mentioned as third factor influencing discomfort. The probable vibration sources in a turboprop are the engine, blade passage frequency (BPF), air conditioning system, boundary flow, and aircraft mechanical systems (Bagherzadeh & Salehi, 2021), and vibration is a major contributor to the internal cabin noise. Although the seated human is especially sensitive to vertical vibration in the 5-10 Hz range, vibration and shock should be attenuated as much as possible, as in practice the lower and higher frequencies might influence

the feeling of comfort as well (Wilder et al. 1994), especially at low magnitudes (Morioka & Griffin, 2006). The seat and seat cushion materials play an important role in attenuating high frequency vibration. New designs that have vibration absorption capabilities with lighter sustainable materials might improve the passengers' comfort in the sustainable aviation of the future.

### **Light and Temperature**

For the total comfort experience light and temperature are important as well. Temperature is often mentioned in the literature regarding comfort (Bazley, 2015). Ranging from 21°C to 31.7°C on continental flights, the temperature in an airplane cabin varies significantly (Pang et al., 2014). The temperature does not only vary between flights, it varies also at different heights in the cabin, among which simultaneous cold feet and hothead discomfort is a frequent complaint (Park et al., 2011). Aircraft cabins can also be cold during boarding, before engines are started, if the aircraft has had time to lose heat since its previous flight. Providing passengers with the right means to control their body temperature (e.g., nozzles and blankets) might contribute to a better comfort experience, the crew can play a role as well in controlling the temperature and the ventilation system.

### **All Factors**

Although the outcomes of this research suggest optimizing the cabin interior for noise or anthropometry and using a hierarchical order of factors influencing (dis) comfort, Bouwens (2018) discusses that optimizing every single element in the environment is probably not wise. Mellert et al. (2008) show that neck complaints are more noticed in noisy airplanes and McMullin (2013) showed that passengers rated their seats better (while these were the same) in the Boeing 737 sky interior compared with a traditional Boeing 737 interior. Hiemstra-van Mastrigt (2015) suggested that people could be distracted from discomfort by having a nice conversation. Kahn (2003) discusses that the presence of background noise is considered positive by train riders, as it masks other sounds like conversations between other passengers. In addition, a strong stimulus might create 'masking effect' regarding comfort (Huang and Griffin, 2012). Therefore, the combination of factors should be studied. But since, in this situation the impact of noise on discomfort is shown to be highest of all factors in a turbo-propeller airplane and on longer flights (more than 70min. as in the test) this impact might be even larger. It is wise to treat noise with higher importance and first reduce the noise to a level mostly influencing comfort and not discomfort.

A disadvantage of researching comfort and discomfort factors with questionnaires is that participants might not be aware of the single causes

and their interdependency for their discomfort or comfort. Often humans are not aware of the environment (Vink, 2014), and in the process of becoming aware of elements in the environment mistakes can be made, like in the already mentioned study of Mellert et al. (2008) where noise was not remembered and neck pain and swollen feet were experienced instead. Another example is the already mentioned study of McMullin (2013). On the other hand, other studies show the importance of anthropometrics in the economy class of jet airplanes and noise in turboprops as well. Apparently, these are relevant matters.

Overall, in fact many factors influencing comfort and discomfort should be taken into account, as they are not independent and might even compensate each other. Further research is needed in this field to see how these factors interrelate. Aggerwal et al. (2021) showed that with the increase in noise levels and vibration magnitudes the overall human discomfort increased, indicating a cross-modal interaction. For the other factors these kinds of studies are needed as well to understand the interaction between different factors and their relationship with comfort. Further analyses will be done in the ComfDemo project and will include comfort evaluations, passengers' attitude and preconditions with reported (dis) comfort factors to show a more complete picture

## **Conclusion**

In designing new electrical propeller aircrafts attention is needed for the sound in the cabin. There are ways to reduce the noise with noise cancelling or by designing the sound to be less unpleasant. In propeller and jet airplanes the seat and pitch need attention in relationship with the anthropometrics. For anthropometrics, there is enough knowledge on what the comfort scores are of various economy class pitches and seat widths. However, many factors influencing comfort and discomfort should be taken into account, as they are not independent and might even compensate each other.

## **Acknowledgement**

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## **2.2. How do we sleep? towards physical requirements for space and environment while travelling**

### **Abstract**

To establish guidelines for sleeping space in vehicles, the sleeping postures of 189 participants are studied, 105 of them were asked to take the position in which they fall asleep and 84 have been asked to assume the position in which they lie most of the time. Seven percent slept on the stomach, 19% on the back and 74% on the side and 49% slept on the side with both legs flexed. For all participants a bed size of 200x90 cm will do. It is discussed that for one night while travelling a bed size of 171x76 cm might be sufficient as it results in a reasonably good sleep according to another study and in almost half of the cases in this study people sleep on the side with both legs folded. Apart from the sleeping space for a good sleep, attention is needed for a dark environment with a good temperature and relative silence.

## Introduction

Passengers want to sleep while travelling. Eighty percent of the aircraft passengers like to sleep on long haul flights (Bouwens et al., 2018), sleeping is among the top four activities observed in trains (Groenesteijn et al., 2017) and occupants of automated driving cars like to spend a part of their time sleeping as well (Wilson et al., 2022). However, sleeping in vehicles has some downsides due to space restrictions. Sleep facilities in vehicles (such as aircrafts, trains, busses, ships, submarines, (automated) cars) often have a limited space due to vehicle design, economic and/or operational reasons (Smulders, 2018; Stanglmeier et al., 2020). For the future self-driving car, a dimension of 191 x 66 cm is reported by Caballero-Bruno et al. (2022). The dimension of a navy rack is 182x76 cm (<https://www.fleetsheets.com/blogs/ship-rack/what-size-bed-is-a-navy-rack>, August 1<sup>st</sup>, 2024). Sleeper trains in Europe recorded by Out (2024) are for instance 174 x 66 cm, 183 x 70 cm and 200 x 75 cm and in business class aircrafts dimensions could be 188 x 66cm and 208 x 53 cm (<https://suitesmile.com/blog/2020/05/09/business-class-beds-visualised/>, August 1<sup>st</sup> 2024). The question is if these dimensions are large enough to facilitate postures to have a comfortable sleep. People do like to sleep as people can feel recovered after sleeping while travelling and this might be a way to spend the time effectively in order to arrive rested. This might be one of the reasons why business class travellers are willing to pay more as they have the privilege of a good sleep, partly due to a full-flat bed, which was introduced in the airline industry in 2000 by British Airways and followed by many airlines.

There are more environments where there is a restricted space for a sleep, like in submarines, ships, busses, crew rest areas and micro hotels. Of course, many aspects of sleep and dreaming have been studied extensively (De Koninck et al., 1983). There are minimal standards for sleep facilities in safety critical environments such as aircrafts (Simons & Spencer, 2007), but no guidelines exist on minimal sleep space envelopes in relation to sleep comfort. To establish guidelines, it might be helpful to estimate the bodily positions assumed during sleep and the dimensions needed to facilitate these sleep positions. This received little attention in the scientific literature.

De Koninck et al. (1983) studied the body postures while sleeping. They observed 200 participants and used only 16 participants for deeper analysis. Also, the study is more than 50 years old, but still relevant. The BBC reported on body postures (BBC, 2003). However, the source and number of participants is not known. More recently, Skarpsno et al. (2017) studied sleep positions and movements with the use of accelerometers, 363 men and 301 women were tested. They reported: *'During their time in bed, participants spent 54.1% (SD 18.1%) in the side*

*position, 37.5% (SD 18.2%) in the back position, and 7.3% (SD 12.3%) in the front position. Increasing age and BMI were associated with increased time in the side position and a proportional reduction in time in the back position'*. There is some research on the effect of the backrest angle on the quality of sleep. Roach et al. (2018) studied the sleep quality of six subjects while lying on a flatbed (180°). Nichol森 and Stone (1987) studied nine participants. Aeschbach et al. (1984) studied 11 participants lying flat. Caballero-Bruno et al. (2022) tested sleep in a 177° backrest angle (almost flat) while driving in a van in a laying on the back position. In all these studies no data on the needed space was given, which is very relevant for a bed design. Smulders & Vink (2021) presented data on dimensions using 41 participants. They slept in three different conditions: night 1) in their normal bed space, night 2) in a limited space (170 x 70 cm), and night 3) in a minimal space which the participant could design themselves. Night 2 was rated least comfortable, where night 1 was most comfortable. However, no significant difference in sleep quality and sleep effectiveness between the normal bed (night 1) and the minimal space designed by the participant (night 3) were found, although space on average was reduced by 25%.

Most beds in Europe are 90, 100 and 120 cm wide for single beds and 200 cm long (Consumer Media, 2019). For areas with restricted space this is too much as it is economically not feasible, but it is unknown what is really needed for a comfortable sleep. This paper aims to gather information on the space people need in areas where the space is limited to support designers and engineers of those areas in designing beds in restricted spaces. This study also gathers information on other environmental requirements needed for a good sleep while travelling.

### **Research questions:**

*What physical space do humans use while sleeping and which environmental conditions do also play a role for humans to have a good sleep while travelling?*

## **Methods**

### **Participants and protocol**

To answer the research questions two studies were performed. One study consisted of asking 75 students as part of a master course to take a position on their bed in which they normally get to sleep and measure the dimensions in x-axis (width of the bed) and y-axis (length of the bed) of their body. The measurement was done using a measuring tape or using the smart phone. They were also asked to put a camera or smart phone on the ceiling and take a picture of themselves in that posture and send it in. They were also asked to measure and follow the same procedure using someone else, preferably an

older person. Adding elderly was done as much data in the literature are based on the age category of students. Additionally, they were asked to complete the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989) for themselves and let the other person complete it. Also, a questionnaire was added with general information on gender, body height and age and there were three open questions in which they were asked to write what will hinder them if they want to sleep in a car, train or airplane. For each type of travel, they had to answer this open question. This had to be completed by the participant and the other person that was invited to participate.

The experimental setup and the protocol were approved by the Human Research Ethical Committee (HREC) of Delft University of Technology and consent forms had to be signed by all subjects. In the consent form there was the option to opt out. No reason had to be given for opting out and no effect on the grade for the course was ensured as assignments were given a score before checking the consent form.

In the second study an additional group of 105 students was approached and asked to record themselves during sleep with a camera on the ceiling. They were asked to use a timelapse system, which records every 10 or 15 minutes as checking a complete video of 8 hours would take too much time and send in a picture of the most seen posture. Additional information was asked regarding gender, body height and age as well. This part was approved as well by the HREC of the TU-Delft and an informed consent was used as well.

All data were stored on a secured TU-Delft server and data are only accessible by the TU-Delft researchers involved in the study and staff/teachers of the TU-Delft involved in the course. An overview of the data is available at <https://data.4tu.nl/>. The body height of the participants is not given in the data base but categorized to prevent that individuals can be traced.

### **Data analysis**

All x-axis and y-axis data will be put together in one graph and all pictures were observed by two persons and categorized in: 1. lying on the side with two legs bended; 2. lying on the side with one leg bended, 3. lying on the side with two legs stretched, 4. lying on the back and 5. lying on the front (stomach). Three times differences were found between the two observers (all considering the situation: both legs stretched or bended; after discussing it was decided to classify these three as bended, as the legs were not completely stretched).

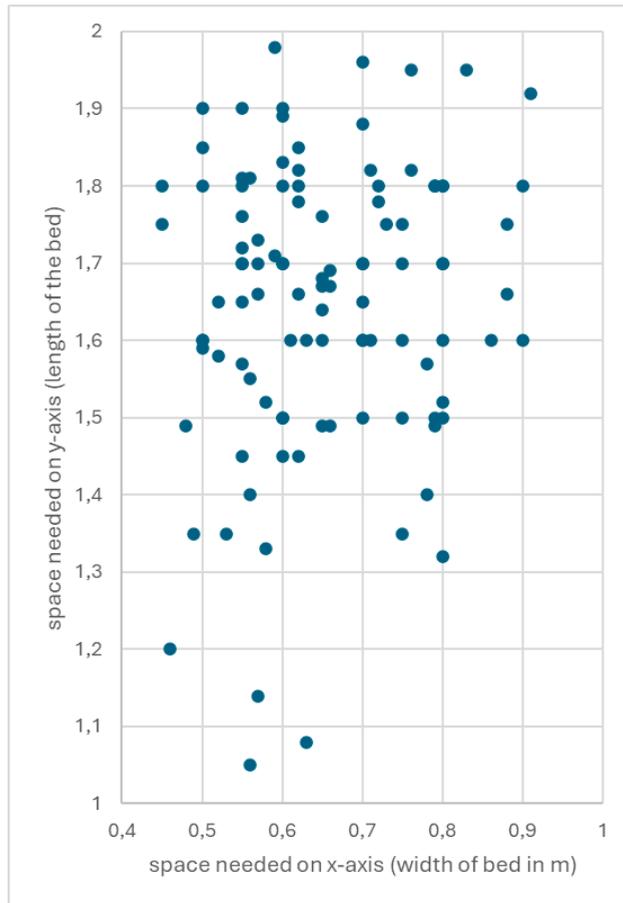
Differences between situations were tested using the t-test ( $p < .05$ ). It was assumed that elderly stretch more, therefore it was tested whether the elderly

group (older than 35) needed more length (more y-axis). Also, it was assumed that the laying in the side would give a higher PSQI score than the one observed sleeping on their back as De Konick et al (1983) state that poor sleepers spend more time on their back. It was also tested if elderly take other positions than the younger persons as Skarpsno et al. (2017) found more side sleepers among older persons.

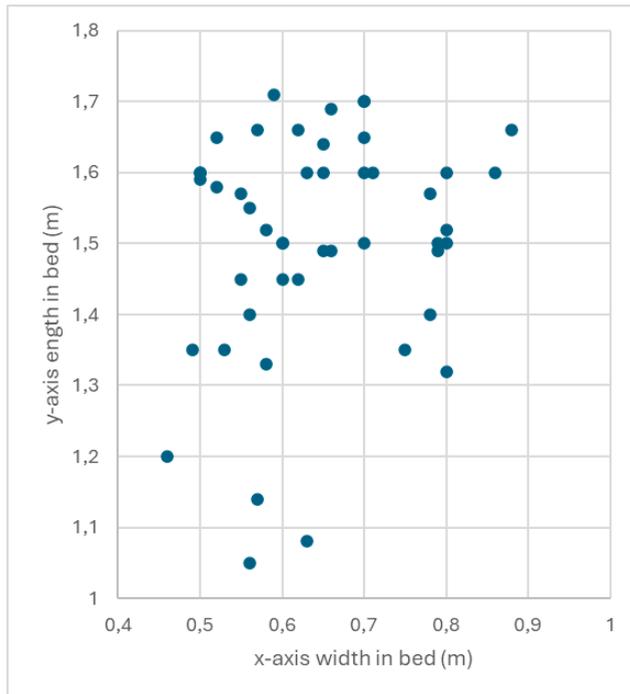
## Results

In the first study, out of the 75 students 52 did sign for opt in and were able to find a second person. So, the first study consisted of 104 participants of which 30 participants were in the age between 40 and 67 years old (average 57 (STD 5.5); average body height 173 cm (STD 9.8; 16 male, 14 females; 32 Asian; 68 European and 4 from other countries). The other (younger) 74 participants had an average age 24.6 years old (STD 2.9; average body height 173.8, STD 10.8; 32 males; 41 female and 1 other). No significant differences could be found between the younger and older group regarding, sleep posture, length needed and PSQI scores. Also, between the back laying posture and side ward sleepers no significant difference in PSQI could be found.

Between the side sleepers and back sleepers there was a significant difference in bed length ( $p=.0001$ ;  $t=4.16$ ). The participants sleeping on the side needed on average 1.60 m (STD .189) on the y-axis and those sleeping on the back 1.78 m (STD .113). In Figure 2.2.1 all data on the space needed on the x-axis and y-axis are shown. 95% of this population fits within .88x1.9 m in this posture. If we take the size of 1.70 x .76m of Smulders & Vink (2021) 39% would fit in this posture. If we take the persons lying on the side with both legs flexed and exclude the persons with their arms above their head for this group a space of 1.71 x .88 m would do (see Fig. 2.2.2)



**Figure 2.2.1.** Data on space needed by the 104 participants in the position when they go to sleep.



**Figure. 2.2.2** the space needed by the persons lying on the side with both legs flexed (the 3 with their hands above the head are excluded, n=48)

In Figure 2.2.3 the data in the answers to the open questions are shown. These results are estimates of the participants as it is unknown how much experience the participants have while sleeping the car, train or airplane. Noise/sound is mentioned most in hindering a good sleep, especially in the train this is seen as a problem. In the car, movement is mostly mentioned as an issue hindering a good sleep. One participant mentioned "frequent cornering and shaking disturbs sleeping". Space prevents sleeping in the airplane and often leg room is reported as the cause. Temperature is mentioned also frequently. One participant mentioned "cold feet hinder sleeping" and another "it's too hot in the airplane". In the car there is no issue with other people, but in the train and airplane talking from other people or people passing by is seen as a problem. Smell is also mentioned as a problem in the train, like "smelly food" or "passengers not smelling well". Light is often too bright for a good sleep and in posture/position it is mentioned that sleeping while sitting upright is a challenge.

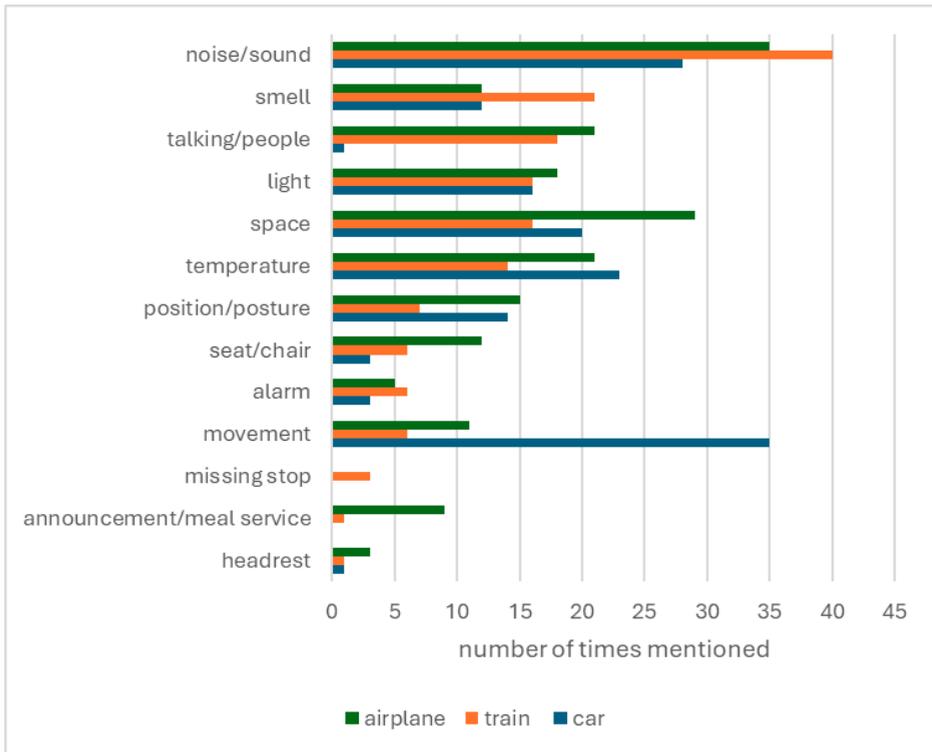


Figure. 2.2.3 Counted topics found in the answers to the question “which factors could disturb your sleep in an airplane/train/car “. Data from the answers to the open questions

In the second study 105 participants were invited. They used a time lapse of every 10 minutes (59) and 15 minutes (40) and in some cases (6) a camera which takes a picture every 10 minutes (2) or every 15 minutes (4). However, in 20 cases participants were not able to define the posture which is seen the most as the bed sheet and blanket or duvet blocked the view too much in combination with a dark environment. Out of the 105, 85 did report the most common posture. Also, 6 out of these 85 reported that they estimated the posture and send in a drawing of what might have happened under the duvet (see Fig 2.2.4). The rest did send in a picture (see Fig 2.2.4).



**Figure. 2.2.4.** Example of a drawing (left) and a picture (right) that was submitted by the participants

The average age of the 85 participants of the second study was 23.3 (STD 2.25) year and the average body height was 172.9 m (STD 9.23; 20 males participated, 64 female and 1 other; 13 Asian; 71 European and 1 from another country).

The postures in bed are shown in Table 2.2.1. The most frequent observed posture is on the side with two legs bended followed by on the side with one leg bended and one leg stretched. If we combine all lying on the side situations, this is observed 74% of the cases. The third most observed posture is lying on the back (19%). There are not many differences between the two studies as can be seen in Table 2.2.1. Perhaps lying on the back is a bit less observed when comparing the most frequently seen posture with the getting to sleep position (13% vs 19%).

Table 2.2.1. The sleep positions observed in the two studies categorized in 5 groups. The first study (n=104) is based on the sleep positions on how people get to sleep. In the second study (n=85) participants are asked to take the most observed sleep position.

|                             |                  |  |  |  |  |  |
|-----------------------------|------------------|---|---|---|---|---|
|                             |                  | lying on the side with two legs bended  | lying on the side with one leg bended   | lying on the side with two legs stretched   | lying on the back   | lying on the front  |
| all 189                     | %                | 49%   | 22%   | 4%  | 19%   | 7%  |
| 104 pp go to sleep position | %                | 49%   | 20%   | 5%  | 22%   | 4%  |
|                             | n=               | 51  | 23  | 5   | 23  | 4   |
|                             | mean body height | 174(10.4)   | 173 (9.3)   | 188(10.0)   | 171(10.2)   | 171(8.96)   |
|                             | mean age         | 31.4(13.8)  | 35.5 (15.0)   | 39.2(22.7)  | 37(16.6)  | 30.7(15.5)  |
|                             | mean PSQI        | 68%   | 64%   | 75%   | 68%   | 61%   |
| 85 pp most seen position    | %                | 46%   | 22%   | 2%  | 13%   | 11%   |
|                             | n=               | 41  | 20  | 2   | 12  | 10  |
|                             | mean body height | 172 (8.0)   | 172 (10.6)  | 185(14.1)   | 173.5(9.66)   | 176(8.95)   |
|                             | mean age         | 23.7 (2.57)   | 23 (2.11)   | 23 (1.4)  | 23.3(1.97)  | 22.9(1.54)  |

## Discussion

Regarding the question what physical space humans need to sleep, a bed size of 200x90 cm is safe if we want to give the space to 100% of the population of this study. However, in the study of Smulders & Vink (2021) no significant differences in sleep quality and sleep effectiveness between the own bed and a smaller space designed by the participant were found. This space on average was reduced by 25% (which was in their study a space of 166x76 cm). The 48 participants in our study lying on the side with both legs flexed needed 171x88 cm. Approximately half of our participants took this position. So, a bed length of 171 cm would do for half of the participants in this study and will give a reasonably good sleep according to the study of Smulders & Vink (2021). If we use DINED.nl and estimate the hip angle on the side at 45 degrees and the knee angle at 90 degrees, the body height of p95 Dutch population 20-60 years would be (sitting height +  $\sqrt{(\text{popliteal height}^2 + \text{buttock knee depth}^2)}$ ): 169 cm.

The Dutch are relatively tall, so a bed length of 171 mm would accommodate sideward sleeping with two legs flexed to a majority of people. The width of their bed in this position was in this study mostly determined by the position of the arms. Some even stretch one of the arms in the x-axis direction. The majority fits within the 76 cm determined by Smulders and Vink (2021).

The conclusion from this study is that for the perfect sleep for everyone a bed of 200x90 is needed, but for half of the population of this study 171x76 might do and for the total population this gives a fairly good sleep based on the study of Smulders & Vink (2021). For vehicles where the sleeping space is limited and where people only spend one night this might be a good solution. Comparing this with a navy rack the width seems just sufficient, but for the smaller train beds, car bed and business class flat beds mentioned above, the 66 cm width could be a problem for a comfortable sleep.

The assumption that laying on the side would give a higher PSQI score than the one observed sleeping on their back was not affirmed in this study as no significant difference could be found, while De Koninck et al (1983) stated that poor sleepers spend more time on their back. Perhaps a larger sample is needed to support this statement or PSQI might not be sensitive enough and more objective measurements like ECG are needed.

Also, the finding of Skarpsno et al. (2017) that older people lay more on the back is not found in this study, but perhaps the sample size in our study is too small.

Comparing the sleeping postures of this study to those of De Koninck et al. (1983) and data published by the BBC (2003), there is some similarity (see Table 2.2.2). Most people sleep on the side. However, De Koninck et al. (1983) reported more front and back sleeping positions. They recorded the mean percentage of time spent in two nights, which might have caused the difference. The results of our study show more similarities with the BBC data that were gathered by Idzikowski. However, the scientific base for this study is not described, which makes it hard to compare. In all studies it is clear that almost half of the population sleeps sideward with both legs folded. Skarpsno et al. (2017) recorded more time sleeping on the back and less on the side. This could be due to the self-reporting in our study. However, the BBC data show even lower on the back sleeping percentages, but it should be mentioned that the total in the BBC data is 89%, which means there are positions not reported.

Table 2.2.2. Comparison of percentage of sleeping positions of this study with other studies.

| sleeping position | De Koninck (1983) | Idzikowski (BBC) (2003) | Skarpsno (2017) | this study |
|-------------------|-------------------|-------------------------|-----------------|------------|
| front             | 11.5%             | 7%                      | 7.3%            | 7%         |
| back              | 32%               | 13%                     | 37.5%           | 19%        |
| side              | 56.5%             | 69%                     | 54.1%           | 74%        |
| both legs folded  | 46%               | 41%                     | -               | 49%        |

Previous studies also stress other factors important for a good sleep. He & Vink (2020) report that factors like privacy, hygiene and neighbours play a role in having a good sleep. Privacy was also mentioned by Kantelaar et al. (2022) in night trains. Also, in this study other persons are mentioned as a disturbing factor for sleep. Bouwens et al. (2018) describe that apart from the physical factors of fitting in the aircraft seat, factors like noise, temperature, light, smell and vibration influence the comfort during sleep as well (presented in the order of importance). These factors are mentioned by our participants as well, except for vibration. Perhaps a part of the vibration is in the category 'movement' mentioned by our participants. Vledder et al. (2023) did mention that movement in the form of Jerk could be an influential factor on sleep in a night train 'It was found that for sleeping comfort and quality, vibration, vehicle speed/movement, and noise levels on sleep should be balanced, and abrupt changes in any factor, e.g. jerk or distinctive sounds should be avoided'. Also based on this research, it should be mentioned that vibration doesn't need to be negative it can also help in the sleep onset. Although in this study it was mainly mentioned as a factor playing a role in cars. Vink et al. (2023) describe on the question 'what do you need for a good sleep?' 55% answered darkness, 33% good temperature and 28% silence, again showing that noise, temperature and light are important factors as well apart from the space needed for a good sleep.

This study also has some drawbacks. All data are self-reported and no validity or reliability tests were done, which is a limitation of this study. On the other hand the study population is large and the outcomes are comparable to other studies and the two studies had different approaches and resulted in similar outcomes. The majority of the population is around 24 years of age and a small group (30) around 57 years old. Different aged persons could have different sleeping habits. Also, the majority was a European population. The population was also healthy. Less healthy people could have other sleeping positions. Also, the first study considered only the position people get to sleep and the participants were asked to take this position, which could have been different in reality. Skarpsno et al. (2017) show that there are on average 1.6 (SD 0.7) position shifts per hour, while sleeping. Therefore, it is the question whether taking the position to go

asleep is representative for the bed size. On the other hand the data have some value as the number of postures observed when falling asleep vary a lot, which is comparable to other studies. The second study only considered the most frequent taken position in the night. On the other hand, the study might give indications as there were similarities with two other studies (BBC, 2003 and De Koninck et al., 1983).

For the environmental factors influencing sleep, the participants' reactions were based on previous experiences. Their answers might be depending on the amount of experience they have sleeping in certain mobility modes. E.g. many people sleep in trains, but the things bothering in a normal travel might be different than when using a sleeper train. This should be considered when interpreting the outcomes of this research.

Caddick et al. (2019) are very specific on ideal sleeping conditions. They describe that all forms of noise in the sleep environment should be reduced to below 35 dBA and complete darkness is optimal for sleep. They also describe that the optimal ambient temperature varies based on humidity and the bedding microclimate, ranging between 17 and 28 °C at 40–60% relative humidity. It shows that apart from size: darkness, silence and a good temperature are important for a good sleep, factors that are also mentioned by our participants. This study shows that for travel situations, the bed area could be reduced while still being acceptable for a 'reasonable' night's rest. Additionally, the fact that legs are folded in many cases, gives opportunities in shaping the bed accordingly.

## Conclusion

To facilitate all sleeping positions for the majority of people a bed of 200x90 cm is preferred. For one night while travelling a bed size of 171x76 cm might do as it allows sideward sleeping and in almost half of the cases people sleep on the side with both legs folded. Apart from the sleeping space, for a good sleep attention is needed for providing a dark environment with a good temperature and relative silence, which includes prevention of disturbance by neighbours, and which takes into account the movement of the vehicle.

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CHAPTER



# PERSON

The previous chapter focused on the influence of the environment on comfort and discomfort. This chapter will take a closer look at the person as a factor influencing comfort and discomfort (Fig. 1.3). The person is not only a factor influencing the experience of comfort and discomfort, but comfort and discomfort are also caused by the way a person handles or acts and is therefore a source as well. In human-centred research, the person is, in fact, always part of the main research question, therefore making this chapter even more relevant.

In comfort research, stature and body mass can have a major influence on the experienced (dis)comfort, e.g., when a tall person is sitting in a seat where there is limited leg space. Therefore, it is important to (pre)select or include a valid representation of a population based on anthropometric measurements, which requires an insight into the accuracy of self-reported stature and body mass (section 3.1). In section 3.2, sleeping postures and sleeping movements are researched during upright napping. During a 90-minute nap, sleeping postures and movements are observed. Additionally, comfort is measured after the nap with questionnaires. Section 3.3 continues to explore the human posture in an upright and reclined seated position, defining the participant's spinal curve in these different positions. The sections 3.2 and 3.3 offer actionable outcomes for designing ergonomic backrests that support diverse users and their postures.

This chapter is based on the following articles:

1. Kılıç, H., Vledder, G., Yao, X., Elkhuisen, W. S., Song, Y., & Vink, P. (2023). Recruiting participants for ergonomic research using self-reported stature and body mass. *WORK: A Journal of Prevention, Assessment & Rehabilitation*, 76(4), 1509–1517. <https://doi.org/10.3233/WOR-220565>
2. Vledder, G., Singh, U., Sabater Compomanes, R., Kılıç, H., Smulders, M., Song, Y., Vink, P. (Manuscript submitted for publication) Impact of Seat Back Recline Angles on Sleeping Posture and Perceived Sleeping Comfort. *Applied Ergonomics*.
3. Bokdam, A., Vledder, G., Song, Y., Vink, P. (Manuscript submitted for publication) Human Back Contour Modeling for Backrest Design in Automated Vehicles. *Applied Ergonomics*

### 3.1. Recruiting participants for ergonomic research using self-reported stature and body mass

#### Abstract

**Background:** A valid distribution of key anthropometric parameters among participants is often a prerequisite of ergonomics research.

**Objective:** In this paper, we investigated the accuracy of self-report stature and body mass of a sample of the population in the Netherlands.

**Methods:** Data from 4 experiments was synthesized where in each experiment, participants self-reported their stature and body mass prior to being measured, of which they were not notified before.

**Results:** Statistical analysis of 249 records indicated that on average, participants overreported the stature by 1.31 cm and underreported their mass by 1.45 kg. This is especially true for people with a  $BMI \geq 25$ .

**Conclusion:** Two models were proposed to adjust the self-reported stature and body mass for ergonomic researchers in a survey or recruitment. Limitations in using the models are highlighted as well.

## Introduction

In the context of ergonomics research, the anthropometric measurements of participants are often a prerequisite. Self-reported techniques are often used to collect information on the stature, the body mass, and the calculated body mass index (BMI, in kg/m<sup>2</sup>) during survey and recruiting subjects. In different (online) surveys, the height and body mass can be important factors in evaluating physical activities, perceptions, etc. (Turrell et al., 2021)(Watson & Wooden, 2012). For instance, Liu et al. asked the height and the body mass of 90 participants via questionnaires for studying comfort of seats in a staggered configuration (Liu et al., 2021). In an online survey designed by Srinivasan et al. on the topic of college students' personality under the impact of COVID-19 online classes, self-reported height and body mass of 897 subjects were collected as well (Srinivasan et al., 2021). To recruit subjects for an experiment, following the requirements and within the practical constraints, researchers often try to ensure a sparse distribution of key measurements, e.g. the stature, the body mass, among the participants to reduce the specificity of the target group and ensure the quality of the research (Roebuck et al., 1975)(Anjani et al., 2021). For instance, in evaluating comfort of an economy seat, researchers tried to select 97 test subjects out of 125 applicants based on the self-reported stature and body mass (Vink et al., 2022). Besides, a better estimation of the actual stature and body mass based on self-reported data might accelerate the process of ergonomics experiments and reduce the cost. Measuring anthropometrics consumes valuable time and manpower. Extensive measurements are seen as "tedious and time consuming" (Dianat et al., 2018). For improving the accuracy, researchers also need to conduct prior-training sessions and repeatable measurements are often taken (Bravo et al., 2018), which both cost extra time and efforts.

Literature supports the theory that the body mass can be underreported and the stature can be overreported in different contexts (Maukonen et al., 2018). For instance, women under-reported their mass by a mean of 0.91 kg in the Health Initiative Observational Study (Luo et al., 2019), and men overreported their height by 1.22 cm on average in National Health and Nutrition Examination Survey (Spencer et al., 2002). However, there are also reports indicating that such self-reported body mass and stature were accurate enough in different studies, e.g. Hodge et al. suggested that BMI computed from self-reported weight and height is a valid measure in men and women across different socio-demographic groups (Hodge et al., 2020). Kee et al. also reported the high correlation between self-report mass and stature with direct measurements in the adolescents group (Kee et al., 2017).

The accuracy of the self-reported stature and body mass is influenced by many factors, e.g., the types of survey, the social-demographic contexts, the sex. The existence of self-stigma regarding the body mass (Pakpour et al., 2019) could influence the subjective ratings in ergonomic studies as well. In research on comparing three different survey data, Flegal et al. found that self-reported height, weight, BMI, and obesity prevalence were not identical across the National Health and Nutrition Examination Survey, the National Health Interview Survey, and the Behavioral Risk Factor Surveillance System, particularly for women (Flegal et al., 2019). Gugushvili & Jarosz also found that women living in rural areas were likely to overestimate their height (Gugushvili & Jarosz, 2019). Maukonen et al. also showed that for overweight and obese participants, the bias was generally higher than those of average weight. Regarding cultural background, the bias was larger in North America, while in Asian studies the bias seemed to be lower (Maukonen et al., 2018). For instance, Xie et al. found that the stature was overestimated at an average of 0.42 cm, but there were no significant differences regarding the body mass and blood pressures between self-reported and measured data in Hong Kong (Xie et al., 2014). Meanwhile, the stature and the body mass of a subject are not static during the day. Vuvor and Harrison found that the mean stature variation from 7am to 7pm was about 1.61 cm (Vuvor & Harrison, 2017). The average mass fluctuation of a person in a short term, e.g. a day or several days, can also be 1 to 2 kg (Bhutani et al., 2017).

While the accuracy, the reliability and the associated factors are still in debate, the self-reported measurements are the easiest, or sometimes the only way, for acquiring the basic anthropometric parameters in the survey and selecting participants in ergonomics research. In this paper, we aim at building models to estimate the actual stature and body mass based on of the self-reported data of adults recruited in the Netherlands in the context of ergonomic research. The outcomes might help ergonomics researchers in using self-reported stature and body mass for survey and recruitment in ergonomics studies.

## Materials & Methods

We collected data from 4 ergonomics experiments conducted in the Faculty of Industrial Design Engineering, Delft University of technology. All experiments focused on evaluating comfort of participants, but in different contexts as: Exp.1) flying with a turboprop aircraft (Nov. 2021), Exp.2) experiencing jet and turboprops noise (February, 2022), Exp.3) sitting with different postures (March, 2022) and Exp.4) sitting in train and aircraft seats (June 2022). In those experiments, participants self-reported their stature and body mass prior to being measured, of which they were not informed beforehand. For instance, in Exp.4 an ergonomics research context was created on the topic of evaluating the

comfort experience of sitting in train and aircraft seats (see Fig. 3.1.1). A large room divider was placed in the middle and anthropometric measurement tools were placed at another side of the room divider. Participants were invited to the experiment in different timespans of a day across 3 weeks. They were instructed to approach from the ergonomics research area where the anthropometric measurement tools were invisible to them. After acquiring the informed consent, participants were asked to fill in a questionnaire about their sex, age, nationality, stature and body mass. Then a researcher led them to another side of the room divider where the basic anthropometric measurements were taken.



Figure 3.1.1: Setup of a typical experiment

All study protocols were approved by the human research ethical committee at Delft University of Technology. Respectively under ID number 1823 (Exp.1), 1953 (Exp.2), 1228 (Exp.3), and 2248 (Exp.4). It is worth mentioning that participants were free to withdraw at any moment of the experiments and his/her data (if any) was destroyed on-site. From the 4 experiments, we collected 76, 15, 28 and 130 valid samples, resulting a total of 249 records. In Exp.1 approximately half of the participants were measured between 08:30 and 09:30, the other half was measured between 12:30 and 13:30. During Exp.2 all measurements were made between 13:00 and 13:30. For Exp. 3 measurements were made in the afternoon. Exp.4 started at 09:00 and lasted until 18:00. G\*Power calculation indicated that for identifying small effects (0.3) of paired samples using Wilcoxon signed rank test in a two-tails setup, 154 samples were needed at the power of 0.95. The 249 valid records were analyzed by statistical tools using a self-developed Python program. All participants took off their shoes and jacket and no extra adjustments, e.g. weight of clothing (Dijkshoorn et al., 2011), were introduced as

interviews of the participants revealed mixed scenarios regarding self-weighting. Based on statistical analysis results, different groups were highlighted.

## Results

Table 1 presents the descriptive statistics of each experiment result as well as a whole. All participants were adults and their mean age is about 28 years. There are high correlations between the self-reported and the measured stature (0.981), and between the self-reported and the measured body mass (0.967). However, people overreported their stature by 1.31 cm on average, and underreported their body mass by a mean of 1.45 kg. Subsequently, the difference of BMIs based on self-reported data and the measured data is about 0.82 kg/m<sup>2</sup>. Regarding individual experiments, Exp.2 and 3 were targeting at the international population and in Exp. 1 and 4, the Dutch population was the majority. Though populations differ, Mann-Whitney U test indicated that there was no statistically significant difference ( $p>0.01$ ) regarding BMIs calculated based on the self-reported data and the measured data between Dutch and International populations. Therefore, all experiment data were combined together in the following analysis.

Table 3.1.1: Descriptive statistics of the collected data

|   | Exp. 1       | Exp. 2       | Exp. 3      | Exp. 4       | All experiments |
|---|--------------|--------------|-------------|--------------|-----------------|
| Total Number  | 76           | 15           | 28          | 130          | 249             |
| Gender (Female/Male)                                  | 49/27        | 9/6          | 13/15       | 66/64        | 137/112         |
| Age   | 33.42±14.02  | 26.33±3.66   | 27.82±2.89  | 25.15±9.15   | 28.04±10.87     |
| Nationality (NL/INT)                                  | 32/44        | 4/11         | 1/27        | 93/37        | 130/119         |
| Mass (kg, self-reported)                              | 71.40±12.40  | 69.87±16.07  | 62.29±9.98  | 71.54±12.57  | 70.36±12.75     |
| Mass (kg, measured)                                   | 73.11±13.33  | 71.73±17.05  | 62.14±10.66 | 73.13±12.97  | 71.81±13.49     |
| Mass difference (kg)                                  | 1.71±3.19    | 1.86±4.45    | -0.14±3.33  | 1.59±3.40    | 1.45±3.43       |
| Stature (cm, self-reported)                           | 177.31±10.63 | 171.00±10.45 | 168.02±6.60 | 177.19±10.30 | 175.82±10.50    |
| Stature (cm, measured)                                | 176.24±10.49 | 169.76±9.28  | 166.03±6.94 | 175.87±9.90  | 174.51±10.28    |
| Stature difference (cm)                               | -1.06±2.29   | -1.24±3.40   | -1.99±1.53  | -1.31±1.78   | -1.31±2.05      |
| BMI (kg/m <sup>2</sup> , based on self-reported data) | 22.61±2.74   | 23.70±3.95   | 21.99±2.78  | 22.66±2.54   | 22.63±2.73      |
| BMI (kg/m <sup>2</sup> , based on measured data)      | 23.43±3.11   | 24.64±4.10   | 22.49±3.24  | 23.53±2.92   | 23.45±3.10      |
| BMI difference (kg/m <sup>2</sup> )                   | 0.83±0.95    | 0.94±1.66    | 0.50±1.23   | 0.87±1.17    | -0.82±1.15      |

Bland-Altman plots (Fig. 3.1.2) on the stature and the body mass affirm the differences. The stature difference is 0.74% higher than the mean value while the body mass difference is about 1.93% lower than the mean. Normality test results indicated that the distribution of the differences does not follow the normal distribution. Wilcoxon signed rank test results showed that the differences of the self-reported and the measured stature ( $p<0.01$ ), body mass ( $p<0.01$ ) and BMI ( $p<0.01$ ) are statistically significant.

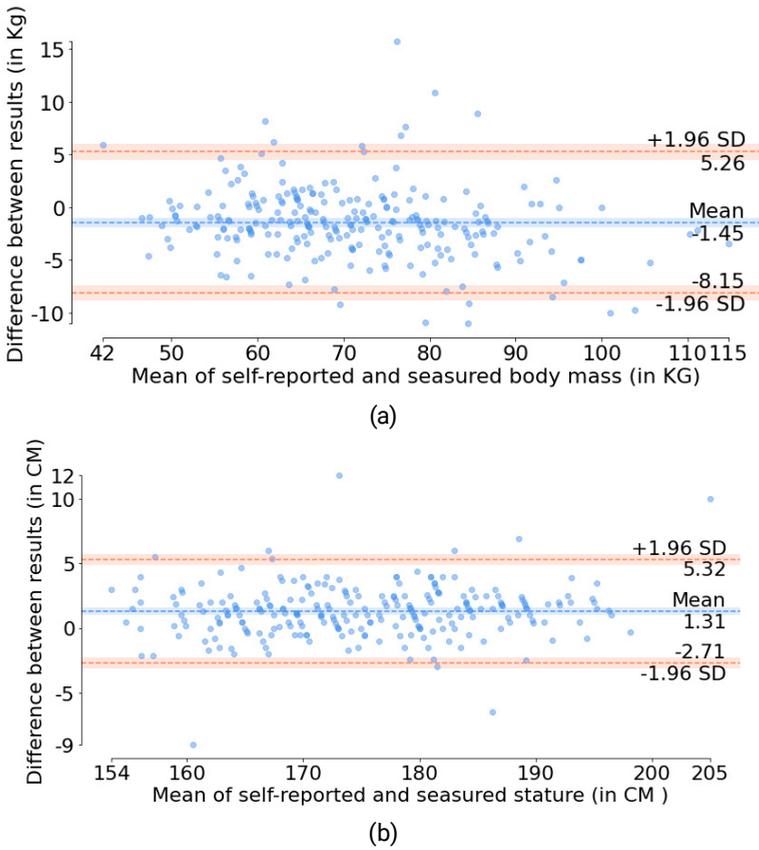
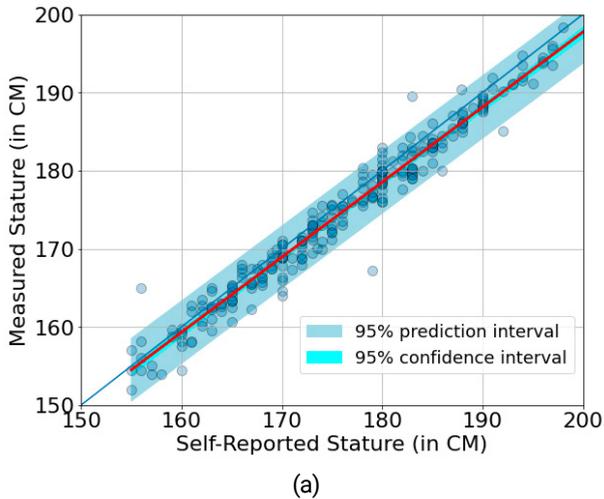
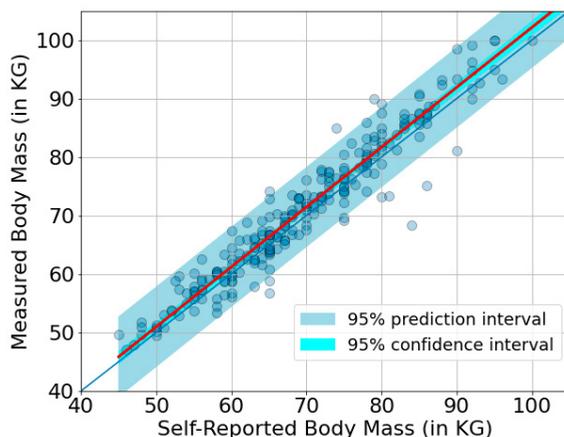


Figure 3.1.2: Bland-Altman plots of the self-reported stature (a) and body mass (b) and regarding the means of using the two methods





(b)

**Figure 3.1.3: The regression model (red lines) regarding the data**

Figure 3.1.3 presents two regression models where the 95% prediction and 95% confidence intervals are highlighted as well. In the model, the measured stature can be calculated from the self-reported stature as:

$$\text{MeasuredStature} = 0.96375 * \text{SelfReportedStature} + 5.36 \quad 1$$

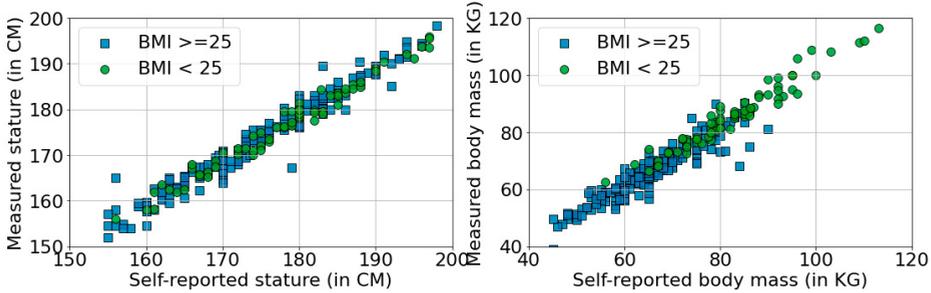
with a root mean square error (RMSE) of 2.24 CM.

For the body mass,

$$\text{MeasuredMass} = 1.04469 * \text{SelfReportedMass} - 1.48 \quad 2$$

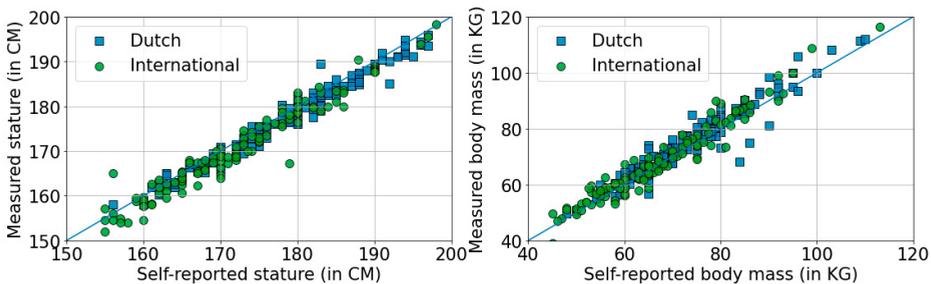
and the RMSE is 3.12 Kg.

Though all experiments were conducted in the context of ergonomic research, different factors, e.g. sex, nationality and BMI, might have influenced the accuracy of the self-reported stature and the body mass. We categorized the data by sex, nationalities and BMI where for BMI, the Centers for Disease Control and Prevention (CDC) recommendation (BMI < 18.5 is underweight, between 18.5 and 24.9 is healthy, between 25.0 and 29.9 is overweight and larger than 30.0 is obesity (CDC, 2022) was adopted. Mann-Whitney U test results indicated that there was not statistically significant difference in those groups except the mass difference of the BMI < 25 group (180 subjects, mean = -0.76kg) was significantly smaller ( $p < 0.01$ ) than the BMI  $\geq 25$  group (69 subjects, mean = -3.24 kg) as Fig. 3.1.4 shows.



**Figure 3.1.4: Measured stature and body mass vs the self-reported body mass and stature regarding different BMI groups**

There are statistically significant differences of the measured stature and the body mass between the Dutch and the international groups. The mean stature of the Dutch group is  $177.79 \pm 9.17$  cm versus  $170.93 \pm 10.26$  cm of the international group. Regarding the body mass, the values are  $75.23 \pm 13.31$  kg and  $68.03 \pm 13.75$  kg for Dutch and international groups, respectively. However, we did not find statistically significant differences between the self-reported data and the measured data for both groups as shown in Fig. 3.1.5.



**Figure 3.1.5: Measured stature and body mass vs the self-reported body mass and stature regarding Dutch & International groups**

Literature indicated that sex and BMI are two important factors of the accuracy of the self-reported stature and body mass, we categorized all data using these two criteria as Table 3.1.2. It can be found that for the self-reported stature, all groups are within the accuracy of 2 cm where women are slightly better than men (1.02 cm vs 1.55 cm). For the body mass, in general men are slightly more accurate than women (-1.24 vs -1.70 kg), but for the BMI 18.5-24.9 groups, both men and women are quite accurate. The largest difference was observed for men and women with  $BMI \geq 25$  groups, where the mean body mass differences

were found as -2.95 kg and -3.5 kg, respectively. Though the mean difference of women is higher than that of the men, it is not statistically significant ( $p>0.01$ ). Regarding nationality, Dutch men and women BMI $\geq$ 25 groups underreported the mass about 2.70 and 3.66 kg, and for the International BMI $\geq$ 25 groups, the values are 3.50 and 3.89kg, respectively.

Table 3.1.2: Differences of self-reported mass and height regarding measurement for different groups

| <b>BMI</b>         | <b>All groups</b>  | <b>&lt;18.5</b>    | <b>18.5-24.9</b>   | <b>25-29.9</b>     | <b>&gt;30</b>      |
|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| <b>Men</b>         |                    |                    |                    |                    |                    |
| No.                | 137                | 1                  | 92                 | 37                 | 7                  |
| Mean Stature       | 180.37 $\pm$ 8.50  | n/a                | 179.81 $\pm$ 8.71  | 182.51 $\pm$ 7.52  | 178.57 $\pm$ 8.75  |
| Mean Mass          | 77.49 $\pm$ 13.26  | n/a                | 71.43 $\pm$ 8.71   | 89.13 $\pm$ 8.32   | 101.24 $\pm$ 10.80 |
| Mean BMI           | 23.74 $\pm$ 3.26   | n/a                | 22.03 $\pm$ 1.61   | 26.73 $\pm$ 1.35   | 31.68 $\pm$ 1.36   |
| Stature Diff.      | 1.55 $\pm$ 2.16    | n/a                | 1.38 $\pm$ 2.24    | 1.92 $\pm$ 2.03    | 1.71 $\pm$ 1.90    |
| Mass Diff.         | -1.24 $\pm$ 3.85   | n/a                | -0.50 $\pm$ 3.94   | -3.03 $\pm$ 2.79   | -2.53 $\pm$ 4.03   |
| BMI Diff.          | -0.77 $\pm$ 1.19   | n/a                | -0.48 $\pm$ 1.07   | -1.45 $\pm$ 1.05   | -1.27 $\pm$ 1.71   |
| Stature Diff. in % | 0.87% $\pm$ 1.21%  | n/a                | 0.78% $\pm$ 1.28%  | 1.05% $\pm$ 1.08%  | 0.93% $\pm$ 1.05%  |
| Mass Diff. in %    | -1.28% $\pm$ 5.11% | n/a                | -0.56% $\pm$ 5.40% | -3.34% $\pm$ 2.98% | -2.28% $\pm$ 3.86% |
| BMI Diff. in %     | -0.90% $\pm$ 1.56% | n/a                | -0.66% $\pm$ 1.54% | -1.60% $\pm$ 1.13% | -1.15% $\pm$ 1.66% |
| <b>Women</b>       |                    |                    |                    |                    |                    |
| No.                | 112                | 2                  | 85                 | 22                 | 3                  |
| Mean Stature       | 167.34 $\pm$ 7.30  | 173.40 $\pm$ 9.90  | 166.93 $\pm$ 7.36  | 167.79 $\pm$ 6.37  | 171.60 $\pm$ 11.75 |
| Mean Mass          | 64.85 $\pm$ 10.11  | 55.25 $\pm$ 6.43   | 61.32 $\pm$ 6.95   | 75.64 $\pm$ 6.58   | 92.20 $\pm$ 12.23  |
| Mean BMI           | 23.11 $\pm$ 2.89   | 18.34 $\pm$ 0.05   | 21.97 $\pm$ 1.66   | 26.83 $\pm$ 1.25   | 31.22 $\pm$ 0.64   |
| Stature Diff.      | 1.02 $\pm$ 1.88    | -1.40 $\pm$ 1.41   | 1.02 $\pm$ 1.98    | 1.03 $\pm$ 1.47    | 2.40 $\pm$ 0.95    |
| Mass Diff.         | -1.70 $\pm$ 2.82   | -0.25 $\pm$ 0.64   | -1.13 $\pm$ 2.67   | -3.50 $\pm$ 2.42   | -5.53 $\pm$ 2.74   |
| BMI Diff.          | -0.89 $\pm$ 1.10   | 0.20 $\pm$ 0.51    | -0.68 $\pm$ 1.00   | -1.56 $\pm$ 1.01   | -2.61 $\pm$ 0.95   |
| Stature Diff. in % | 0.61% $\pm$ 1.14%  | -0.79% $\pm$ 0.77% | 0.62% $\pm$ 1.21%  | 0.61% $\pm$ 0.88%  | 1.39% $\pm$ 0.49%  |
| Mass Diff. in %    | -2.43% $\pm$ 4.30% | -0.52% $\pm$ 1.21% | -1.77% $\pm$ 4.38% | -4.67% $\pm$ 3.36% | -5.87% $\pm$ 2.45% |
| BMI Diff. in %     | -1.31% $\pm$ 1.67% | 0.31% $\pm$ 0.90%  | -1.09% $\pm$ 1.67% | -2.09% $\pm$ 1.42% | -2.82% $\pm$ 0.83% |

Table 3.1.3: Comparison of this study and some previous studies

| Reference                 | Stature difference<br>(in cm/%) |            | Mass difference<br>(in kg/%) |              | Context  | Country                      |
|---------------------------|---------------------------------|------------|------------------------------|--------------|--|------------------------------|
|                           | Men                             | Women      | Men                          | Women        |  |                              |
| (Stewart, 1982)           | 2.08                            | 1.07       | -0.726                       | -1.406       | Health Insurance Study                                       | USA                          |
| (Spencer et al., 2002)    | 1.23                            | 0.60       | -1.85                        | -1.40        | European Prospective Investigation into Cancer and Nutrition | UK                           |
| (Krul et al., 2011)       | 1.7                             | 1.1        | -0.4                         | -1.1         | The CAESAR project 1999-2000                                 | Italy, NL and North America. |
| (Dijkshoorn et al., 2011) | 0.8                             | 0.8        | -0.9                         | -0.8         | Amsterdam Health Monitor 2004 survey                         | NL                           |
| (Bowring et al., 2012)    | 0.3                             | 2.3        | -1.00                        | -2.8         | Survey in a music festival                                   | Australia                    |
| (Tolonen et al., 2014)    | 0.7                             | -0.6       | -1.3                         | -1.4         | European Health Examination Survey                           | 12 EU countries              |
| (Hodge et al., 2020)      | 0.48                            | 0.16       | -1.55                        | -0.88        | Cancer prevention study                                      | USA                          |
| This study                | 1.55/0.87%                      | 1.02/0.61% | -1.24/-1.28%                 | -1.70/-2.43% | Ergonomics studies   | NL                           |

## Discussion

In this paper, we investigated the accuracy of self-reported stature and body mass regarding the anthropometric measurements within the ergonomics research context in the Netherlands. Experiment results support the declaration that people slightly overreport their stature and underreport their body mass, which is in accordance with some studies in Table 3.1.3. This is especially true for people with  $BMI \geq 25$ , where statistically significant difference regarding the self-reported and the measured body mass was identified with a mean difference of -3.24 kg. Compared to a previous study on the Dutch population (Dijkshoorn et al., 2011), the difference of the stature and the body mass are slightly larger, which might be that we did not introduce extra adjustments. However, it is in accordance with the review conducted by Maukonen et al. (2018), where large BMI population tends to report less on their body mass.

Although the time of measurements for all experiment is known, the time and date of self-reported measurements are unknown. Vuvor & Harrison found that the daily stature variation of adults aged  $\geq 30$  years is as high as 1.61cm (Vuvor & Harrison, 2017). Reilly et al. indicated that the peak variation of the stature can be 1.93cm or 1.1% of the overall stature (Reilly et al., 1984). 71% of the height gained during the night was achieved in the first half of the night's sleep, and over 50% of the height loss in a day happened in the first hour of rising, and 80% was lost within 3 hours of arising. Considering the time of the experiment, e.g. Exp.2 and 3 took place after 3 hours of arising, the main decrease in stature changes already happened. The identified mean difference of the stature is 1.31cm, which is slightly larger than 50% of the peak variation.

Regarding the body mass, Turicchi et al. found that there are weekly, seasonal and Christmas patterns where within a week, the mean body mass fluctuations are 0.35% (Turicchi et al., 2020). Whigham et al. indicated that the average clothing weight throughout the year was significantly greater in men ( $1.2 \pm 0.3$ kg) than in women ( $0.8 \pm 0.3$ kg) (Whigham et al., 2013). Besides, the timing for defecation (median 0.128 kg/cap/day) and urination (median 1.42 L/cap/day) might also influence of the measured body mass (Rose et al., 2015). Considering the uncertainty in the self-measurement time and conditions, it can be assumed that for groups with  $BMI < 18.5$ , the self-reported body mass is within the fluctuation ranges. However, for  $BMI \geq 25$  groups, the difference between the self-report body mass and the measurement is larger.

In the measurement results, the mean heights are 180.37 cm and 167.34 cm for men and women, respectively. These are close to the P50 data in the Dutch anthropometric database (DINED, 2011). The smaller standard deviations of

women on the self-reported body mass indicated that women might know their actual body mass better than men, as the self-weight frequency of women is higher than that of men (Gavin et al., 2015)(Hahn et al., 2021).

With the underreported mass, 35% (24 of 69) of the participants in the  $BMI \geq 25$  group (mean  $BMI = 25.9$ ) lowered their reported BMI to the range of  $BMI < 25$  (mean =24.11). The reasons that the self-reported body mass of participants in this group is lower than the measurement might be complicated. Besides sex, nationality, Althubaiti summarized that self-reported bias can also arise from social desirability, recall period, sampling approach, or selective recall these aspects (Althubaiti, 2016). The accordance with literature indicates that the ergonomics research context has little influence on the bias. For recall period, sampling approach, or selective recall, previous research indicated that the self-weighting frequency of  $BMI \geq 85$ th percentile is even higher than that of the  $15$ th  $\leq BMI < 85$ th percentile group (Hahn et al., 2021). Social desirability might be the most influential factor on the bias. The body shape is associated with the self-image of a person, and a positive self-image is an important aspect for people to recognize the assets, the limitations and the potentials, and keep positive motivation on tasks and liabilities. For this, people tend to think towards the positive side on their self-image rather than generate it based on facts, e.g. people are more accurate while their focus is on the external observers (Bašić & Quercia, 2022). This might be more obvious for women, as they are more critical of their body shape (Buote et al., 2011). Therefore, participants with larger BMI might want to report less of their body mass to maintain a positive self-image on the body shape, as in most cases the stature is more a nature and more visible than the body mass.

In summary, participants slightly overreported their height and underreported their mass. The stature differences between the self-reported and measured data slightly exceed the daily fluctuation range of a person. The differences of the self-reported body mass and measured results of the  $BMI < 24.9$  group is within the daily fluctuation range. But for the  $BMI \geq 25$  group, the difference is larger. For ergonomics studies where the anthropometric measurements were not possible, e.g. in survey, in recruitment, it is suggested that the self-reported stature and the body mass can be adjusted using the linear regression models (Eq.1 and 2). In this case, the RMSEs of the differences in the stature and the mass can be reduced from 2.43cm to 2.02cm and from 3.71 kg to 3.42kg, respectively. This is especially useful for the body mass of the  $BMI \geq 25$  group where the RMSE is reduced from 4.37 to 3.06kg. In the experiment, when there are constraints regarding both/either manpower and/or time, the proposed model can be used as a backup tool. However, ergonomics researchers shall be aware of the large RMSEs and risks of peak variations in using this technique,

as the peak variations of the self-reported statures are -5.5% and 7% and for the self-report body mass, they are -12.8% and 22.9%.

This study has several limitations. Most of the International group participants were studying/working in the Netherlands. We did not find significant differences of self-reported data between Dutch and International groups. Maukonen et al. reported a difference between Asian and American studies, which means a comparison study in other countries might find more social-cultural factors that influence the accuracy of self-reported stature and body mass (Maukonen et al., 2018). Though researchers paid extensive efforts in recruiting, the mean age (28.04 years) of participants was young and the number of participants, especially in the BMI<18.5 and BMI > 30 groups, was low compared to other studies that were mainly based on national surveys. This prevented the use of advanced modeling tools to make a more accurate estimation based on more parameters, e.g. gender, measurement time in a day, time duration from the last self-measurement. However, the context of the study is ergonomics research, which casts a new view toward the bias of participants in self-reporting their stature and body mass.

## Conclusion

In this paper, we compared the self-reported stature and body mass regarding the measurements in the context of ergonomics research, and try to provide a tool for ergonomic researchers and practitioners for estimating the actual stature and body mass based on self-reported data. Experiment results supported the findings reported in the literature that people slightly overreport their stature and underreport their body mass, especially in the BMI $\geq$ 25 group. It is suggested that in ergonomic research especially in the survey and recruitment where conducting anthropometric measurement is not possible, or too expensive regarding both manpower and time, researchers can use the proposed models, with the understanding of the limitations, to estimate the actual stature and body mass based on self-reported data, especially for the BMI $\geq$ 25 group.

## Ethical Considerations

All study protocols were approved by the human research ethical committee at Delft University of Technology. Respectively under ID number 1823 (Exp.1), 1953 (Exp.2), 1228 (Exp.3), and 2248 (Exp.4).

## **Informed consent**

All participants involved in this study signed an informed consent form before participating in this study. The informed consent followed the guidelines of the human research ethical committee at Delft University of Technology and was approved by this same committee.

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## **Conflict of Interest**

The authors declare that they have no conflict of interest.

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## **3.2. Impact of Seat Back Recline Angles on Sleeping Posture and Perceived Sleeping Comfort.**

### **Abstract**

Many people like to sleep during transit, but it is not always considered the most comfortable activity, especially in a seated position with limited space, like a car, train, or airplane. This study examines the impact of seat back recline angles (SBAs) on sleeping postures and perceived comfort. Sixteen participants completed six 90-minute naps in a lab across six seating conditions: five recline angles (110°–150°) and a flat stretcher (180°). Comfort and postural discomfort questionnaires, along with posture observations, revealed that greater recline angles improved comfort, reduced discomfort, and limited posture variety. From 110° to 150°, participants predominantly maintained a straight back posture against the backrest and straight legs, while side sleeping with bent legs was preferred on the flat stretcher. Upright angles evoked discomfort-triggered posture adjustments, particularly in the head and legs, whereas reclined angles allowed greater torso movement and enhanced comfort. These findings can support the design of seating solutions for better comfortable sleeping experiences during transit.

## Introduction

Have you ever fallen asleep on a train, airplane, or in a car? Most people would likely answer yes. Studies show that sleep is a common activity during transit. Groenesteijn et al. (2014) identified sleep as the second most frequent activity on medium- to long-distance trains, and Bouwens et al. (2017) noted that many passengers sleep during flights. Sleeping in transit can make time feel more productive and reduce the perceived cost of travel time (Molin et al., 2020). This trend is gaining relevance with automated vehicles, where sleep is expected to become a prominent non-driving activity (NDRA) in Level 4 and Level 5 vehicles (Cai et al., 2024; Molin et al., 2020).

However, sleeping while traveling is not always comfortable. For example, Bouwens et al. (2017) found that in-flight sleeping received the lowest comfort rating among onboard activities, despite comfort being key for passenger satisfaction and rebooking (Heufke Kantelaar et al., 2022; Vink & Hallbeck, 2012). Contributing factors include noise, vibration, light, and limited space. Limited space restricts travellers' ability to adopt ideal sleeping postures, especially upright seated positions, and reduces comfort while sleeping.

Research on sleep medicine has examined sleep disorders, sleep physiology, and treatments (Pierson-Bartel & Ujma, 2024), yet studies on the ideal sleep environment, particularly the ergonomics of upright sleeping, remain limited (Smulders & Vink, 2021). People most of the time sleep laterally (54.1% of time in bed (TIB)), followed by the supine position (37.5% TIB) (Skarpsno et al., 2017). Additionally, 74% prefer a bent-leg side posture (Vink et al., 2025), aligning with NASA's neutral body posture (Kim et al., 2019). People also often change postures while sleeping; De Koninck et al. (1992) reported an average of 3.6, 2.7, and 2.1 position shifts per hour in a normal night's rest in the age groups 18-24, 35-45, and 65-80, respectively. While normal flat beds offer more uniform pressure distributions and freedom of movement, upright seated sleeping configurations limit posture options.

In upright sleep, posture restrictions and limited hip mobility due to seat constraints create additional challenges (Yao et al., 2023). Tan et al. (2009) identified 15 in-flight sleeping postures, with six involving a turned torso, indicating a preference for lateral sleeping positions. Kamp et al. (2011) noted that head, trunk, and arm positions significantly impact sleep, with slouched positions and elevated feet being common, although the backrests remained fixed in one angle. Adjustable backrests can improve sleep comfort and reduce back muscle activity (Goossens et al., 2003). Biomechanically, a backrest recline angle of 155° with a 40° seat pan angle is recommended (Stanglmeier et al.,

2020). Studies have explored the impact of reclined seats on sleep efficiency, which improves with recline angle (Aeschbach et al., 1994; Caballero-Bruno et al., 2024; Hayashi & Abe, 2008; Nicholson & Stone, 1987; Roach et al., 2018). Caballero-Bruno et al. (2022) tested sleeping comfort in a 150° and 177° recline angle. However, research on how varying recline angles affect posture preferences, posture changes, and comfort is limited.

Sleep during travel typically lasts less than 50% of the average major sleep period, as noted by Vink et al. (2023). This aligns with the definition of a nap: A nap is any sleep period with a duration of less than 50% of the average major sleep period of an individual (Faraut et al., 2017). Given the shorter duration of sleep in vehicles, we will specifically address napping throughout our analysis.

This study aims to investigate the relationship among the seat back angle (SBA), sleeping postures, and perceived sleeping comfort. Specifically, we address gaps in how the backrest recline angle affects comfort and posture by exploring the following: (1) Which sleeping postures are most common at different recline angles? (2) How many distinctive postures occur at different angles? and (3) Does a larger recline angle increase comfort?

## Materials and Methods

To address the research question, an experimental study was conducted using five seats with varying SBAs (110°, 120°, 130°, 140°, 150°) and a flat stretcher (180°) as a reference condition. Participants attended six sessions, starting at the same time of day each on different test days. During each session, they slept on one of the seats or the stretcher for a sleep duration of 90 minutes. After each session, participants completed questionnaires, and the sessions were recorded on video for posture observation and classification. Detailed procedures and measurement techniques are described below.

### Participants

Thirty-two participants were recruited, with 16 completing all six setups, achieving a statistical power of 0.9 for detecting large differences between configurations in a one-tailed test. Table 3.2.1 presents the anthropometrics of these 16 participants. Recruitment targeted the student and staff community at Delft University of Technology via social networks and student chat groups. A self-assessment questionnaire was used for selection; individuals with sleep disorders, those who found it “extremely difficult” to nap during the day, or those who snored (to avoid disturbing others) were excluded. Participants with “no specific” or “evening” chronotypes, based on the reduced Morningness-

Eveningness Questionnaire (rMEQ) with scores below 17 (Danielsson et al., 2019), were included.

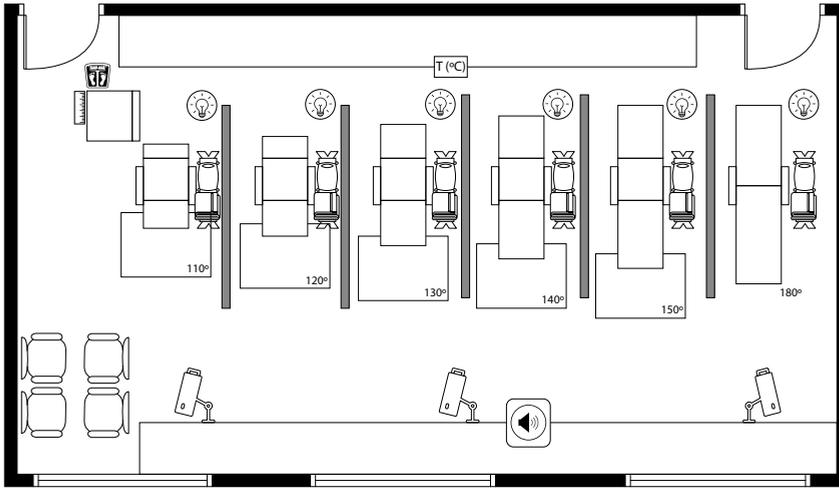
Table 3.2.1 Anthropometry of participants

| Participants [n=16]          | Mean±SD   |
|------------------------------|-----------|
| Age                          | 24.1±3.7  |
| Body mass (kg)               | 65.1±15.7 |
| Stature (mm)                 | 1702±390  |
| Hip width (mm)               | 390±39    |
| Elbow to elbow width (mm)    | 457±54    |
| Shoulder width (mm)          | 427±34    |
| Popliteal height (mm)        | 485±43    |
| Buttock-popliteal depth (mm) | 491±40    |
| BMI (kg/m <sup>2</sup> )     | 22.4±4.3  |

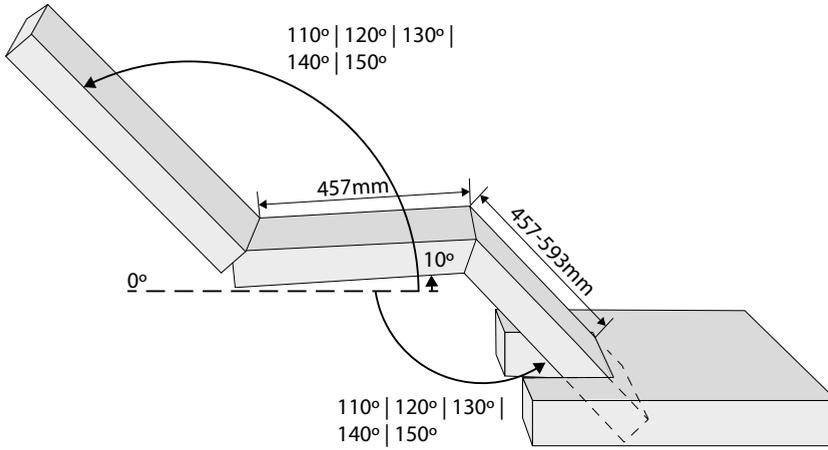
### Experiment setup

The laboratory environment was designed to promote sleep under ideal conditions: cool, dark, and quiet (Caddick et al., 2018). The setup included dimmable floor lamps, privacy screens, and window blinds to maintain a dark, private, and silent atmosphere in a quiet part of the building (Fig. 3.2.1a). Room temperature was controlled between 17°C and 28°C, and participants could adjust their micro-climate using a blanket. To facilitate a gentle wake-up process, lighting was gradually increased at the end of each designated sleep period, accompanied by a two-minute fade-in of natural bird sounds. Three cameras were positioned in front of the participants to capture their sleeping postures.

Five customized seats with adjustable backrest angles (110°, 120°, 130°, 140°, 150°) and a flat stretcher with an angle of 180° were arranged in the lab (Fig. 3.2.1b). Each seat included a backrest (1034 mm x 475 mm), a seat pan (457 mm x 470 mm), and a calf rest, with calf rest lengths varying from 457 to 593 mm. The calf rest angle moved parallel to the backrest angle, causing the varying length when the calf rest moved underneath the footrest. The seat pan was reclined at a 10° angle from horizontal, selected based on findings in the literature (Wang et al., 2024), which indicated that comfort levels did not differ much across different seat pan angles. Manual adjustments allowed researchers to set each backrest angle precisely. Additionally, items for comfortable upright sleep, such as blankets and pillows, were provided (Vink et al., 2023). Figure 3.2.1(c) shows a participant seated with a blanket and pillow, while Fig. 3.2.1(d) provides an overview of the laboratory, with the flat stretcher (530 mm wide, 1900 mm long, 270 mm high) positioned in the foreground as the reference condition.



(a) Floor plan of the lab



(b) The seat



(c) Example of a sleeping scenario



(d) An overview of the experiment with and stretcher in the front

Fig. 3.2.1. Research setup

### Questionnaires

Questions evaluating overall comfort, sleep comfort, SBA comfort, and leg/foot support comfort were asked using a 10-point Likert scale. Additionally, the Local Postural Discomfort (LPD) questionnaire was used to assess discomfort in each part of the body before & after the sleeping sessions (Anjani et al., 2021). Further questions evaluated sleep quality, including: *Did you have a good or bad nap, and can you explain why you had a good or a bad nap? Please identify anything which caused you comfort/discomfort during the nap. How many minutes of actual sleep did you get? Did you manage to sleep during the last 90 minutes?* All questionnaires were presented in English.

### Protocols

Each session lasted approximately 130 minutes. Participants were informed about the study and provided informed consent before the experiment. During the first session, participants' anthropometric measurements were taken. For each sleep period within a session, participants were seated in a systematically varied order. Before the sleep period, while seated, participants completed a questionnaire on their phones. They were then asked to switch their phones to airplane mode and place them in a box to prevent access and avoid distractions. For hygienic reasons, participants were requested to keep their shoes on during the sleeping period.

Each sleep period began at 13:00 and 15:30 daily. A 90-minute sleep duration was chosen to allow participants to complete a full sleep cycle (Carskadon & Dement, 2005), avoiding sleep inertia and the associated negative effects on

comfort that occur when waking during the nREM phase (Cavallero & Versace, 2003; Milner & Cote, 2009). After each sleep period, participants' phones were returned to them, and they completed the same questionnaire on their phones, including the questions as listed in Section 2.3.

### Posture observation and classification

Before observation, postures were predefined and coded using a rapid coding technique for efficient analysis (Branton & Grayson, 1967; De Koninck et al., 1992; Groenesteijn et al., 2014; Kamp et al., 2011). Table 3.2.2 shows the coding scheme, and Fig. 3.2.2 gives an additional visual explanation of the code. Three codes were assigned for head (up, down, neutral), trunk (stomach, back, leaning/rotated to a side), and legs (straight, one or both legs flexed/folded, one or both crossed). Four codes were defined for arms (both straight, both flexed/folded, asymmetric, supporting head with hand or cushion). Additionally, left (1), right (2), and neutral (3) were coded for all body parts, with an extra code for postures that were undefined or not visible due to factors such as darkness or movement under a blanket. Eventually, 8 codes were given: one for each body part as defined in Fig. 3.2.2, and one left/right/neutral score per body part.

Table 3.2.2 Postural position codes

|           | Description   | Code |
|-----------|---|------|
| Head [H]  | Neck extension/Upward   | 1    |
|           | Neck flexion/Downward   | 2    |
|           | No flexion or extension/Neutral   | 3    |
|           | Not visible   | 10   |
| Trunk [T] | Stomach   | 1    |
|           | Back  | 2    |
|           | Asymmetric/leaning to a side (Lateral flexion & extension). Turned torso/ Rotated to the side | 3    |
|           | Not visible   | 10   |
| Legs [L]  | Both straight/parallel  | 1    |
|           | One or both legs flexed/folded*   | 2    |
|           | One or both crossed (crossed at the ankles counts as parallel legs)                           | 3    |
|           | Not visible   | 10   |
| Arms [A]  | Both straight   | 1    |
|           | Both flexed/folded – Both crossed*  | 2    |
|           | Asymmetric  | 3    |
|           | Supporting the head (with hand or cushion)  | 4    |
|           | Not visible   | 10   |

*\*for limbs to be scored 'folded', limb flexion should be approximately 45° or more*

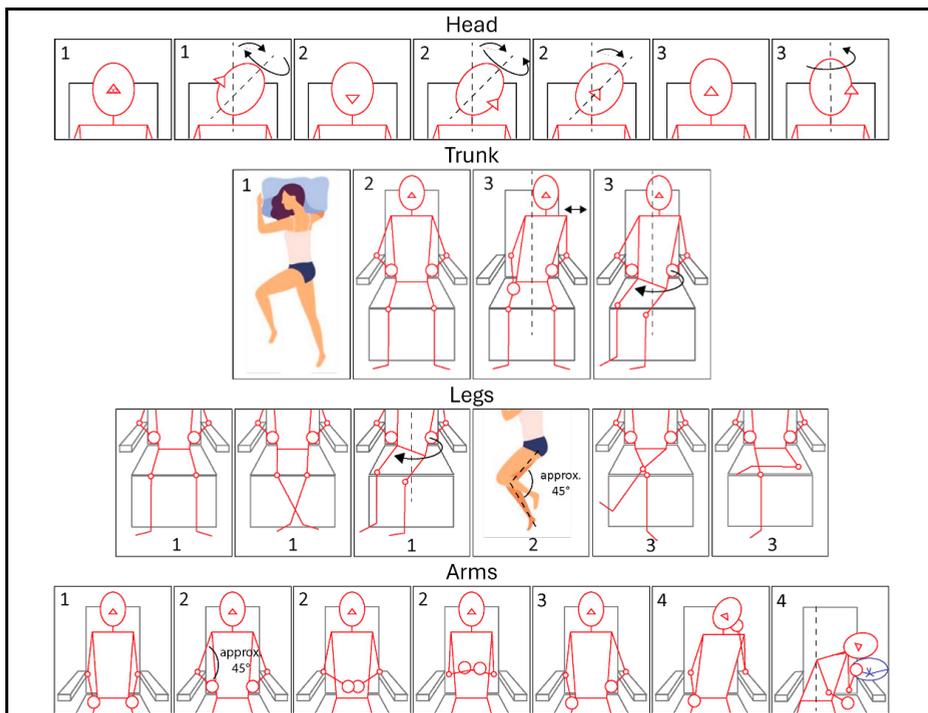


Fig. 3.2.2. Code explanatory pictures

Captured videos from three cameras were sampled at ten-minute intervals, resulting in ten video frames per participant per angle (16 participants x 10 frames x 6 conditions = 960 frames). As not all video recordings were exactly 90 minutes the amount of video frames derived from the recording varied. On average there were 8.7 ( $\pm 1.4$ , min. 3, max. 10) frames per participant per angle observed and analysed. To normalize the data based on the number of frames available per participant per angle, the result analysis was performed using the percentages per participant.

Figure 3.2.3 shows one frame as an example. The left posture in Fig. 3.2.3 was coded as: the head in a neutral direction, and in a neutral position (code 3, 3); the trunk in a neutral direction, and straight-backed (code 3, 2); the legs in a neutral direction, and crossed (code 3, 3); and the arms in the middle, folded (code 3, 2). The right posture in Fig. 3.2.3. was coded as: the head to the left, and downward (code 1, 2); the trunk in a neutral straight-backed position (code 3, 2); the legs in a neutral straight position (code 3, 1); and the arms in a neutral folded position (code 3, 2). Each frame was coded independently by two observers. Observers were trained on the protocol, and any coding differences were reviewed by a third observer. In cases of disagreement among all three, a group discussion was conducted to reach a consensus.



**Fig. 3.2.3: Example of a video frame with the observed posture code.**

Left side picture code: head=neutral 3, trunk=neutral 2, legs=neutral 3, arms=neutral 2 with a SBA of 10°; Right side picture code: head=left 2, trunk=neutral 2, legs=neutral 1, arms=neutral 2 with a SBA of 120°.

### Data analysis methods

A self-developed Python program was used for descriptive and statistical analysis, with text analysis conducted via Atlas TI®. Statistical significance was set at  $p < .05$ . The Shapiro-Wilk test showed that most data (posture differences, comfort/discomfort, and LPD questions) were non-normally distributed, requiring non-parametric tests. For two-sample comparisons, the Wilcoxon Signed Rank Test was used for related samples and the Mann-Whitney U test for unrelated samples (e.g. difference regarding sex). For multiple-sample comparisons, the Friedman chi-square test assessed differences across SBAs in the LPD questions. Self-reported sleep duration and the number of position shifts per hour were normally distributed, therefore a paired t-test was used to compare differences between two samples. The Spearman rank correlation coefficient identified relationships between variables. In performing the spearman rank correlation the percentual occurrence of trunk and leg position codes were used to compensate for a difference in video frames per participant. Some posture observations were incomplete: data for one participant was missing in the 150° condition, and when “not visible” (code: 10) observations were excluded, 140° included one participant less. Thus, for pairwise comparisons involving 140° or 150°,  $n = 15$ ; when both were involved,  $n = 14$ .

The number of position shifts per hour was determined by checking for changes in all scores going from one frame to the next, followed by summing the number of changes across all body parts, dividing by the amount of frames, and multiplying by six to simulate the number of position shifts per hour. Position shifts from e.g., the head, were treated similarly to position shifts of the trunk,

this decision was made based on 'undecided' categorization and definitions of in-seat movements in literature (Kruithof et al., 2023)

## Results

Based on the sleep period of sixteen participants in six different backrest recline angles, an average of 8.7 frames were observed and six different trunk/leg combinations were defined. The number of distinctive postures and the type of postures were defined across all SBAs, and were explored concerning anthropometric data, comfort questions, and local postural discomfort. Additionally, the mean number of position shifts per hour was calculated for each SBA. For all conditions, the number of people who indicated they slept during the test varied between 13 and 14 (out of 16). The average self-reported sleeping time overall conditions (self-reported) was 45 minutes ( $\pm 21.1$ ). The minimum average number of minutes was 42 ( $\pm 26.1$ ) in 120 degrees and the maximum was 48 ( $\pm 21.7$ ) in 140 degrees, but differences between angles were not significant.

### Most observed sleeping postures

Six combinations of trunk and leg positions were identified, and their occurrences in percentage at each SBA angle are shown in Figure 3.2.4, with 'not visible' and left/right/neutral scores excluded. The accompanying posture drawings give an indication of what these postures can look like in a seat, with the note that the drawings are also used for 180°, even though in a flat bed, these postures might look slightly different. The most frequently observed posture across angles from 110° to 150° was having the back against the backrest with legs straight (posture 1) (all observed over 57% of the time). This position accounted for over 70% of the observed postures at the 120°, 130°, and 140° angles. At 180°, participants were equally likely to sleep on their side with their legs pulled up (posture 5, 47%) or on their back with their legs straight (posture 1, 47%).

At 110°, 81% of postures featured the trunk straight against the backrest, but leg positions showed greater variation. In contrast, at 150°, 72% of postures had the back straight against the backrest, with a notable increase (27%) in positions where the trunk was rotated or leaned to the side compared to other angles. While posture 1 remained predominant, posture 3 (back against backrest with legs crossed) showed a slight increase at 110°, and posture 4 (trunk rotated or leaning to the side with legs straight) was occasionally observed at 150° and 180°.

Analysing individual trunk and leg positions, male participants were significantly more likely to sit with their back straight against the backrest (male mean 87%

versus female mean 65%,  $p < .05$ ), while female participants more frequently adopted a posture with the torso turned or leaning to the side (male mean 13% versus female mean 33%,  $p < .05$ ). There were fewer differences in leg positions, with only a significant difference in the 'not visible' (code 10) category: female participants' legs were more frequently obscured from view (male mean 0% versus female mean 5%,  $p < .05$ ), indicating that they often cover their lower limbs with the blanket.

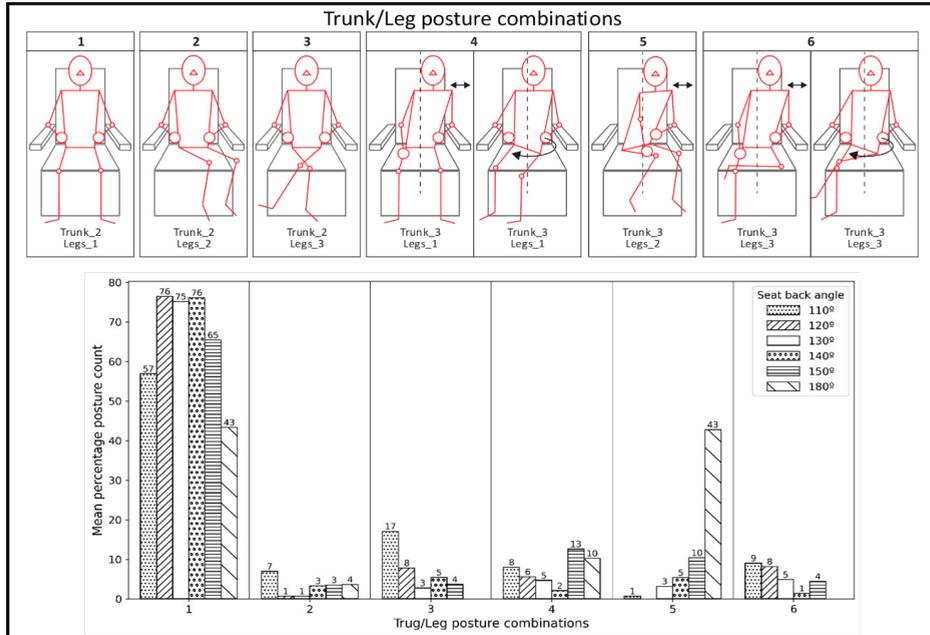


Fig. 3.2.4. A visualization of the six trunk and leg combinations observed and the occurrence (in percentage) of trunk and leg combinations.

### Position shifts per hour

The mean number of position shifts per hour is shown in Fig. 3.2.5 for each SBA, in combination with the significant differences between the SBAs. Participants changed their position more in 110°, 130° and 180°. Where the value in 110° was significantly higher than 140° and 150°, the value in 130° was significantly higher than 150°, and the value in 180° was significantly higher than 150°.

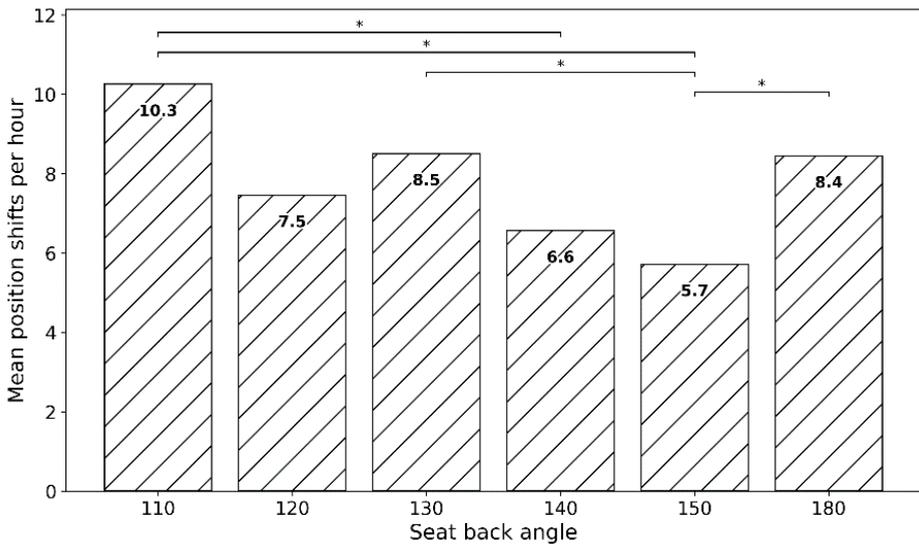


Fig. 3.2.5. Mean position shifts per hour over all angles (\* $p < .05$ ).

#### Amount of distinctive sleeping postures observed per angle.

Figure 3.2.6 illustrates the number of distinctive posture combinations observed at each angle, where 'distinctive posture combinations' refers to the unique sets of postures adopted within each SBA (posture variety), regardless of how often or how long they were held. These combinations include all body parts (head, trunk, legs, and arm) as well as left/right scores and position scores, with 'not visible' scores excluded. Generally, participants in more reclined backrest angles adopted fewer distinctive postures compared to those in more upright angles. The 180° angle had significantly fewer distinctive postures than all other conditions.

When comparing male and female groups, males adopted significantly ( $p < .05$ ) more distinctive postures than females. Additionally, there is a medium-strength (.41) significant ( $p < .05$ ) correlation between the number of distinctive posture combinations and the seat backrest angle.

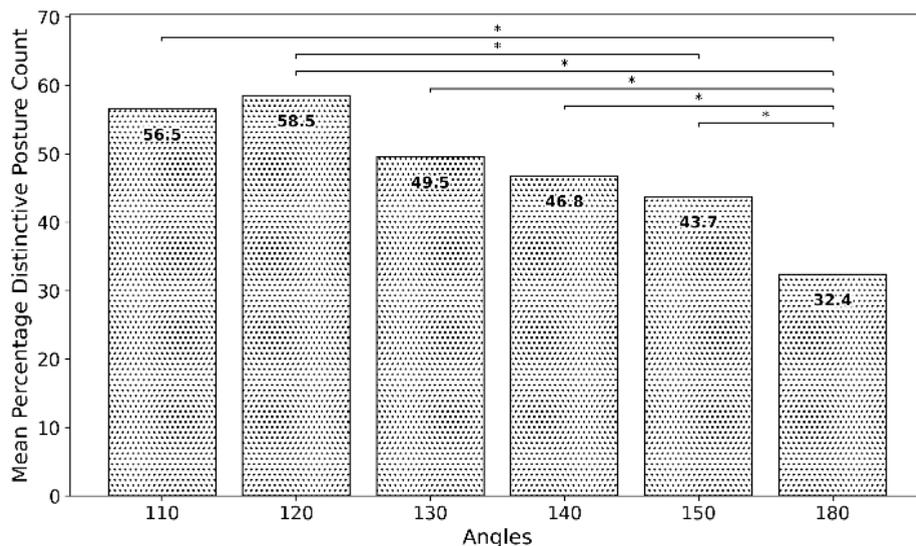
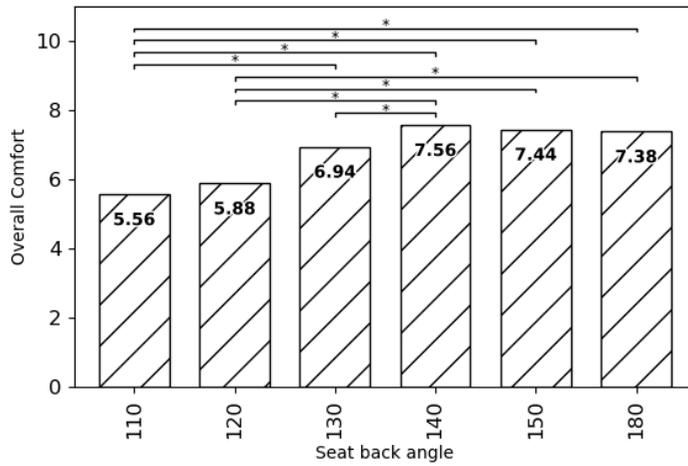


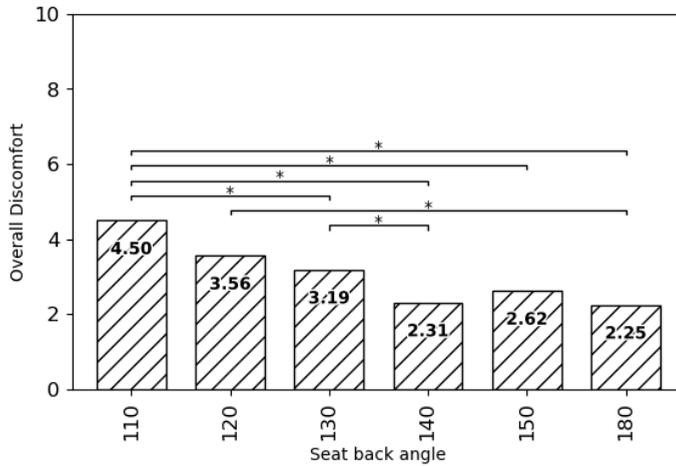
Fig. 3.2.6. Amount of distinctive posture combinations per angle in percentages to compensate for differences in the number of video frames across participants. (\* $p < .05$ ).

### Comfort/Discomfort per angle

The overall comfort and discomfort ratings indicate a clear improvement as the seatback angle (SBA) increased from 110° to 180° (Fig. 3.2.7). Notably, a significant enhancement in overall comfort was observed when transitioning from 110°, 120°, and 130° to 140°. This trend was also evident in the overall discomfort scores. Similar improvements were found in responses to other comfort-related questions focussing on SBA, feet/leg support, and sleep. With increasing angle the SBA, feet/leg support, and sleep comfort increases and discomfort decreases. However, we did not find a significant difference among 140°, 150°, and 180° regarding comfort and discomfort scores.



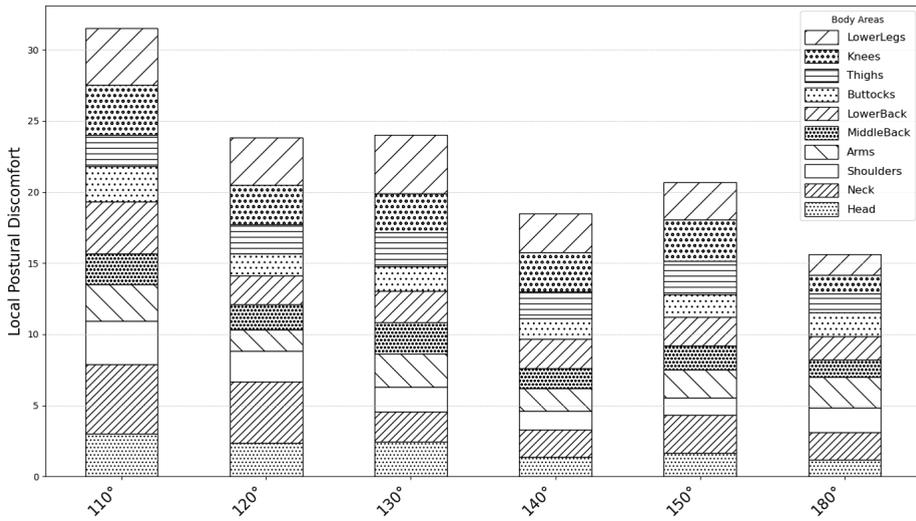
(a)



(b)

Fig. 3.2.7. Mean values of the overall comfort (a) and overall discomfort (b) experience per SBA (\* $p < .05$ ).

The LPD question results (Fig. 3.2.8) show that overall the LPD scores are low (below 5 out of 10). When comparing the LPD mean values over all SBAs (Friedman chi-square); the head, neck, shoulders, lower back, and knees differed significantly. Adding to this, when testing individual comparisons between angles (Wilcoxon Signed rank); the Lower legs in 110° are significantly different compared to 150° and 180°; 120° compared to 180°; 130° compared to 150° and 180°; 140° compared to 180°.



**Fig. 3.2.8. Mean values of the local postural discomfort per body part and SBA.**

In addition to the ordinal comfort and discomfort questions, participants were asked to explain why they had a good nap and to identify what caused their comfort/discomfort during the nap. The responses were combined and clustered into descriptive topics involving seat characteristics and body parts. Table 3.2.3 shows how often each cluster was mentioned. The results indicate that a lack of neck support is the main cause of discomfort, particularly in the smaller SBAs. This is followed by a ‘less comfortable sitting position’ in almost all angles, except 180°. On an individual level, the lack of neck support is an important issue at 110°, followed by the backrest of 110° and the chair size at 180°.

Table 3.2.3 Causes of bad nap and bad comfort/discomfort per angle mentioned by 16 participants in two open questions: 'why did you have a good or a bad nap?', and 'what caused you comfort/discomfort during the nap?'

|  | 110° | 120° | 130° | 140° | 150° | 180° | Total |
|--|------|------|------|------|------|------|-------|
| Lack of neck support                     | 19   | 15   | 8    | 2    | 4    | 1    | 49    |
| Less comfortable position                | 9    | 10   | 7    | 6    | 7    | 2    | 41    |
| Pain in legs/feet                        | 8    | 8    | 9    | 8    | 3    | 3    | 39    |
| Backrest angle                           | 16   | 10   | 3    | 1    | 1    | 1    | 32    |
| Uncomfortable feet/leg support           | 10   | 3    | 5    | 3    | 4    | 4    | 29    |
| Neck pain                                | 8    | 7    | 5    | 2    | 1    | 0    | 23    |
| Difficulty to sleep                      | 4    | 3    | 4    | 4    | 6    | 1    | 22    |
| Chair size                               | 2    | 2    | 1    | 1    | 1    | 13   | 20    |
| Angle does not allow liberty of movement | 2    | 6    | 0    | 4    | 5    | 2    | 19    |
| Waking up during nap                     | 1    | 4    | 4    | 2    | 5    | 2    | 18    |
| Arm rest                                 | 3    | 3    | 1    | 2    | 3    | 2    | 14    |
| Back pain                                | 5    | 3    | 4    | 0    | 1    | 0    | 13    |
| Arm pain                                 | 1    | 1    | 2    | 1    | 0    | 2    | 7     |
| Lack of feet support                     | 0    | 2    | 0    | 0    | 0    | 1    | 3     |
| Total                                    | 88   | 77   | 53   | 36   | 41   | 34   |       |

### Relationships: seat back recline angle, sleeping posture, and sleeping comfort/discomfort

#### *Relation seatback angle with trunk/leg scores and comfort questions*

In Fig. 3.2.9a, the relationships between the SBA and the observed trunk and leg positions (counted occurrence of the code) are presented. Some of these relationships are significantly correlated ( $p < .05$ ) (specifically, Leg 2 and 3, Trunk 2 and 3), with leg score 2 (one or both legs flexed) showing a moderate correlation strength (.44). This suggests that with increasing angle, more participants tend to sit with their legs flexed. Other significant relationships are weaker (correlation  $< .3$ ) but may indicate that at bigger angles, fewer participants cross their legs, and fewer sit with their backs against the backrest or bed. Instead, they may adopt positions that involve more rotation or leaning to the side.

Figures 3.2.9b and 3.2.9c depict correlations between SBA and responses to comfort/discomfort questions and between SBA and the LPD questions for each body part. Interestingly, all discomfort questions show significant

correlations ( $p < .05$ ), while the comfort questions do not. Similarly, all LPD body part scores are significantly correlated with SBA, although none exhibit a strong correlation. Notably, the question on discomfort related specifically to backrest angle demonstrates a moderate correlation strength (-.60), while other discomfort questions display weaker relationships. Among the LPD scores, the head and neck regions have the strongest correlations with SBA (-.28 and -.36, respectively).

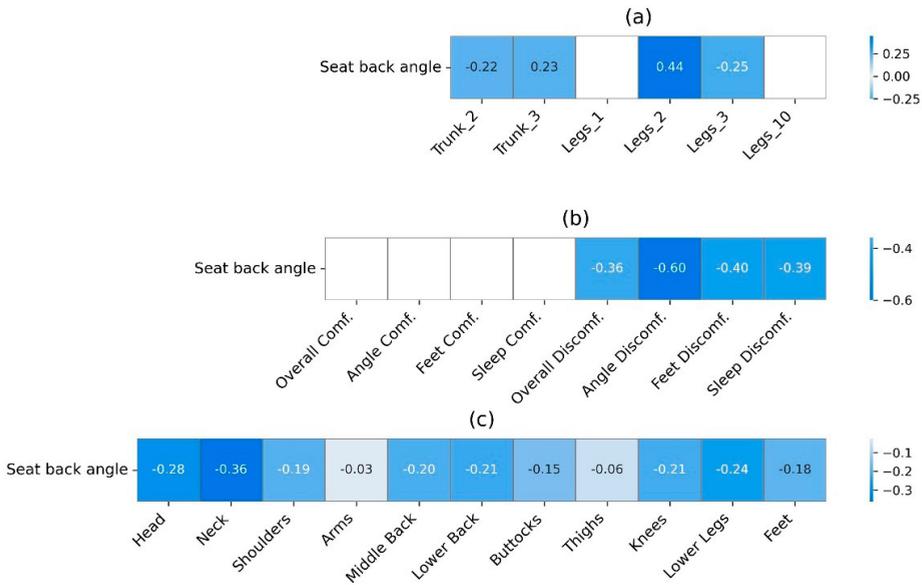


Fig. 3.2.9. Spearman rank correlation comparing the seat back recline angle in connection to the occurrence of trunk/leg positions (a), comfort/discomfort questions (b), and LPD questions (c). Only significant values are shown.

*Trunk and leg scores in relation to anthropometrics*

Figure 3.2.10 illustrates the relationships between the occurrence of trunk and leg posture codes and participant anthropometric data. Overall, there are more significant correlations between trunk/leg positions and anthropometrics at 110° compared to other angles, with the least correlations observed at 180°. The strongest correlations appear at angles of 110° and 120° (above .6/- .6), and therefore in these angles anthropometric measurements seem to have a stronger relation to the kind of trunk and leg postures participants would sit in. In addition to some lower correlations; BMI, elbow-to-elbow width, and popliteal height are notably associated with trunk rotation and crossed-leg positions, particularly at 110° and 120°. Participants with lower BMI are more likely to sit with their legs crossed at 110° (-.77) and 120° (-.63), and to have their trunks rotated at 120° (-.6). Individuals with narrower elbow widths rotate their trunks more at 110° (-.63) and cross their legs more at 120° (-.69). Additionally,

participants with lower popliteal height tend to rotate or lean their trunks more to the side at 110° (-.69).

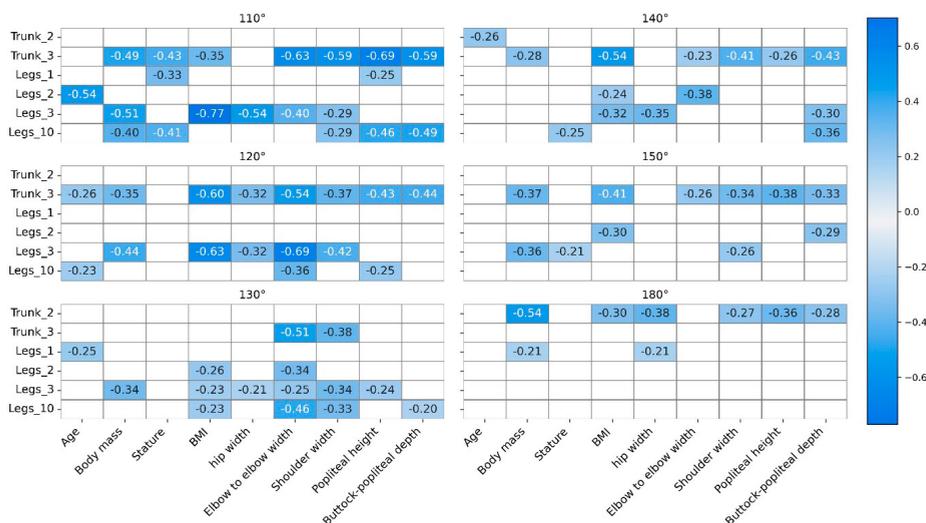


Fig. 3.2.10. Overview of Spearman correlation coefficients of legs and trunk position scores in relation to demographic and anthropometric participant data. Only significant relations with correlation values  $\geq .2$  are presented.

### Head lowered position

As previously mentioned the LPD question outcomes indicate that mean head LPD is the highest at 110°. Additionally, responses to the open questions highlighted the lack of head or neck support as a key factor contributing to discomfort. Figure 3.2.11 displays the percentage of occurrence of each head position across the different angles. The downward head position is more frequent at 110° than at other angles and is significantly negatively correlated with SBA (-.33). Furthermore, in observations of the arm positions; at 110°, participants more often supported their heads with a hand or cushion (22.7%) compared to 120° (11.3%) and 180° (12.2%).

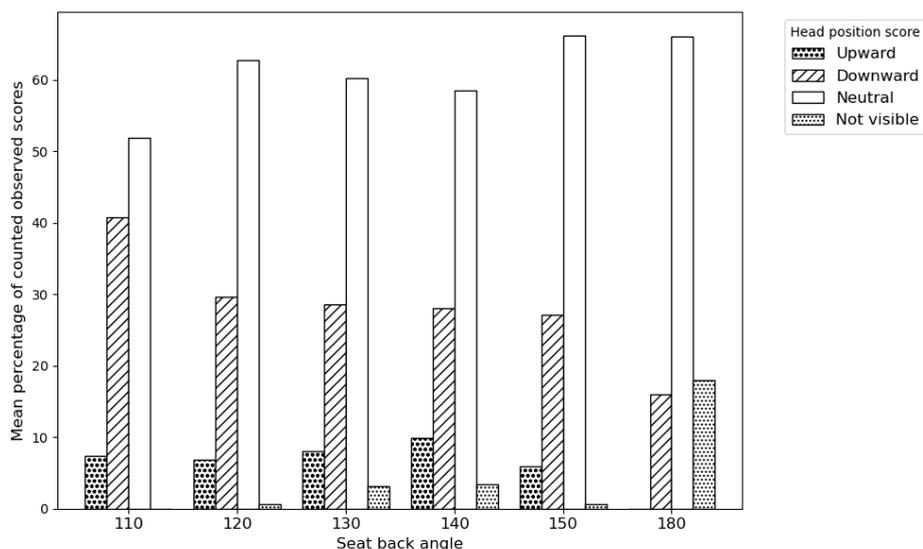


Fig. 3.2.11. Occurrence of head positions taken per angle in percentages.

## Discussion

Answering the research questions, the results indicate a relationship between seat back recline angle, sleeping posture, and sleeping discomfort, though the strength of these relationships varies. Generally, a more reclined backrest angle is associated with increased comfort (according to the pairwise comparisons with the Wilcoxon signed rank test), reduced discomfort, fewer distinctive sitting postures, and a greater tendency for participants to bend their legs while in higher SBAs. From 110° to 150°, the most common sleeping posture observed involves sitting with the back straight against the backrest and legs stretched. Posture variety is higher at angles of 110°, 150°, and 180°; and position shifts (movements) are higher at angles of 110°, 130° and 180°. This does not align with the trend seen in the overall number of distinctive postures, and comfort/discomfort scores; suggesting a deeper explanation is needed. To fully understand this relationship the results are further discussed in this chapter, describing possible explanations.

## Main findings

### *Sleeping postures*

In this study, a sitting posture with the back against the backrest and with straight legs is most observed for upright seated sleeping (110°-150°). Studies show that a supine sleeping position is the second most commonly observed, but the most preferred sleeping posture in bed is side sleeping (Skarpsno et al., 2017; Vink et

al., 2025). A rotated torso for seated sleeping was most comfortable according to Tan et al. (2009). Although the supine position is observed the most in the upright SBAs (if we assume posture combination 1 is the seated equivalent of the supine sleeping posture), this might not be the most preferred sleeping position. The occurrence of the supine position is negatively correlated to SBA. Based on this, it can be hypothesized that as the musculoskeletal system, particularly the capacity for lateral flexion of the spine, accommodates the posture, individuals are more likely to prefer a lateral sleeping position. Although further research is necessary to support this hypothesis. Nonetheless, this position could be specifically addressed when designing seating supports intended to facilitate sleeping. Additionally, at higher angles, more people pull up their legs, and fewer people cross their legs, as also described by Vink et al. (2025) in a 180° bed.

#### *In-seat freedom of movement versus comfort/discomfort*

This study found distinct trends in posture types and movement frequency across different seat back angles. Movement frequency decreases at 110° and increases at 180°. In contrast, the number of distinctive postures decreases progressively from 120° to 180°, and the overall comfort/discomfort improves from 110° to 140°. This pattern aligns with findings by Sammonds et al. (2016), who noted that increased discomfort leads to a higher frequency of seat fidgets and movements. Additionally, Zhang et al. (2025) found that in the lower limbs, switching to a new posture has an alleviating effect on discomfort.

At 110° (and partially at 120°), the seat restricts movement, but the centre of gravity of the head and upper body is positioned more forward compared to the SBAs 120° to 150°. This increases the possibility for head position variation and highlights the need for additional upper-body support, as indicated by higher discomfort scores in the neck area. A reduced “locking” effect in the seat by gravity, and discomfort-triggered adjustments (DTA) to alleviate discomfort at these angles (Yao et al., 2023), leads to greater variety in postures and movements, particularly in the legs. Between 120° and 150°, posture variety and movement shifts decrease, potentially due to improved comfort and alignment of body angles closer to the neutral body position (Kim et al., 2019). The reduced discomfort in these angles reduces the need for frequent adjustments.

At 150°, the increased trunk-to-leg angle allows for more lateral seating postures, although this does not lead to more movements and posture variety. However, at 180°, movement frequency rises again despite fewer distinctive posture combinations. This increase can be attributed to the interplay between freedom of in-seat movement and the movement induced by comfort and discomfort. In fully reclined positions, gravitational forces no longer “lock” participants into

their seats, as in upright seating, leading to increased movement within a limited range of preferred postures.

### *Comfort/Discomfort*

The comfort and discomfort results in this study show a clear increase in comfort and a decrease in discomfort when the SBA increases, although the main improvement seems to take place between 110° and 140°. We did not find significant differences among the setup of 140°, 150° and 180°. Although further comfort improvement was expected, Caballero-Bruno et al. (2024) and Caballero-Bruno et al. (2022) also did not report any significant comfort differences between 150° and 177°. Stagnation of discomfort improvements in 180° could be sought in the mentioned discomfort cause 'chair size'. When the bed parameters of this study are compared with the minimal sleep envelope as suggested by Vink et al. (2025) (171x76cm), the bed width was smaller in this study (53cm). Additionally, a comparison with the home situation might play a role in comfort stagnation, as expectations matter (Naddeo et al., 2015). Leading to higher comfort requirements for a flat sleeping situation.

All discomfort questions, including the LPD results, are significantly correlated with the SBA. This could be seen as a confirmation that discomfort in general is more related to physical factors compared to comfort (Zhang et al., 1996). The strongest correlation is between the SBA and the 'angle discomfort' (-.59). A logical result since this question was specifically directed at checking this physical characteristic of the seat 'the angle'.

## **Secondary findings**

### *Connection between the posture and anthropometrics*

Individual physical characteristics can be of great influence on the experienced comfort. In this research, many correlations were found between anthropometric characteristics and the seated posture, especially in 110° and 120°. There is a clear reduction in correlations going from upright to reclined angles. Indicating that certain physical factors have more influence on postures taken in e.g. 110° and 120° compared to the other angles, for instance limiting the participant to take certain sitting postures. This is in line with findings from Anjani et al. (2020) who found that anthropometric sizes significantly affect the (dis)comfort when the seat pitch is small, and the seat characteristic in this way has a restricting effect on DTA options.

In this study, the legroom was not a limitation, but the seat width could be seen as a restriction. The strong correlation between BMI and the legs crossed posture in 110° and medium relation in 120° could be seen as an indication of this

width restriction. People with a higher BMI sit less often with their legs crossed. The importance of seat width on comfort and freedom of movement was also stressed by Anjani et al. (2021). In all SBAs it seems that many anthropometric variables are correlated to a rotated/leaning to a side trunk position except for 180°. Indicating that in general 'smaller' people have more movement space to move around and thus take other sitting postures than the 'standard' prone sitting position.

The elbow to elbow width is related to offering support to the upper body. Elbow to elbow width and shoulder width (although with less strength) is negatively correlated to a rotated or asymmetric trunk from 110° to 150°. In 110°, 120° and 130° of medium strength. This might indicate that people with narrower shoulders and a smaller elbow to elbow width sit more leaned to the side to reach the armrests. For people with broader shoulders, this distance might be easier to bridge.

#### *Male/Female differences*

Several sex differences were observed. Women overall experience less sleep comfort and more discomfort. Additionally, men tend to adopt more distinctive postures. Skarpsno et al. (2017) reported more movement shifts in males, although we know movement shifts are not the same as distinctive postures. While both groups sit more often in a 'prone' sitting position, women sit more often with their trunk rotated while men sit more often with their back straight against the backrest. This last fact is not in line with findings from Skarpsno et al. (2017), who reported that males spend more time on their side (55.6% of TIB) compared to females (52.2% of TIB). However, those findings were based on a flat-bed situation. Differences in trunk postures, could also be related to differences in stature as in general female participants are shorter than male participants, and trunk rotation was also correlated to stature in 110°.

#### **Design implications**

Based on the overall comfort and discomfort outcomes, a minimal angle of 130° is preferable while sleeping (Vledder et al., 2024). But based on differences in movement shifts or 'DTA' between 110° and 140°/150°, this limit could also be set to 140°. Next to this, the local discomfort is higher in the areas of the neck, knees, lower legs, and feet. This corresponds to findings from Caballero-Bruno et al. (2022), stating that the most discomfort was reported in the head/neck and legs/feet area. The open-question findings can help explain discomfort in these areas, as the lack of neck support and pain in legs/feet or uncomfortable feet/leg support, are explicitly mentioned. In our study only the calf was supported and not the feet. Furthermore, the categories "pain in legs/feet" and "discomfort in feet/leg support" could be combined, as they highlight similar issues. This

highlights the importance of improving leg and foot support to prevent dangling feet and to enhance the sleeping experience.

In this study, the head was supported by the hand or cushion and observed in a downward position more often in the most upright SBAs. The observation of the head in a downward position supports the hypothesis that the head will drop down due to muscle relaxation and gravity when entering deep sleep (Smulders, 2024, p. 232) and possibly in this way waking up the participant when triggering the vestibular system, causing discomfort in the neck area when the head stays in this unsupported downward position for too long. In this study, this last effect is shown by the correlation of the discomfort in the neck area with the angle. Additionally, the lack of neck support is the biggest issue causing discomfort as mentioned by the participants. As suggested in previous research (Bouwens et al., 2018; Vink et al., 2023), this research can confirm that offering head support for upright sleeping will improve sleep (dis)comfort. Therefore if upright sleeping is required, adding head support is very important, and should be seen as a requirement for facilitating an acceptable upright sleeping experience. Bouwens et al. (2018) recommended that future head supports in airplanes should restrict the head movement in yaw, pitch, and roll directions. Further future research could investigate where head support should be placed or is most important for sleeping while sitting in multiple backrest angles.

Enhancements to seating support should prioritize upper body and head support in more upright configurations while promoting posture variation at greater recline angles. Effective upper body support can be achieved through advanced headrest designs and adjustable arm supports accommodating a range of elbow-to-elbow widths. Assuming the preference for side sleeping (in upright sleeping), the design of seating support, including seat width and backrest configuration, should facilitate posture variation across individuals with varying BMIs. To facilitate this incorporating novel seating support characteristics such as the backrest roll angle (BRA) or the entire seating support roll angle (SRA) may provide additional ergonomic flexibility. Furthermore, lumbar support tailored for slouched positions could enhance comfort, as Groenesteijn et al. (2014) observed that although slouched postures are frequently adopted by upright seated sleepers, they are not associated with the highest comfort ratings.

### **Research methods**

Our findings for flat sleeping (180°) correspond partially to earlier literature findings. The side sleeping posture is observed most frequently (when postures combinations 4 and 5 are added together), as suggested by literature (Skarpsno et al., 2017; Vink et al., 2025), and side sleeping in combination with the legs pulled up is observed more often compared with other leg positions (Vink et

al., 2025). However, a prone sleeping posture was not observed, while others report that 7.3% of the time in bed is spent lying on the stomach (Skarpsno et al., 2017). Our research method might provide an explanation. When scrolling through the video footage some people were sleeping prone, as a result of only using video frames/snapshots every 10 min. these positions were overlooked and not reported. Future research should consider including more video frames to be observed.

The analysis in this research mainly focussed on the trunk and leg position. The use of a blanket led to the invisibility of some human body parts, especially the arms were hard to see sometimes. Blankets were included for the facilitation of sleep and temperature regulation. It is also suspected that females use the blanket more often, which might explain the significant difference in observed leg postures (females have more values of 10 indicating it is not visible). For follow-up research, the choice of including a blanket or not should be made again. Otherwise, the usage of movement measurements that are not based on visibility could be considered. Additionally, the focus on the use of trunk and leg positions opens up possibilities for simplification of the chosen codes and classification to further tailor them to the use in 'upright' sleeping and add certain focuses.

While it may be tempting to compare the position shifts per hour reported in this study with those documented in the literature, it is important to note that direct comparisons should be avoided. In this study, we observed one frame every ten minutes and not a continuous recording, no exact time indication can be derived from this method. Therefore the number of position shifts should only be used as a comparison between conditions. Additionally, there are differences in the classification of codes in this research compared to De Koninck et al. (1992). In this study left/right/neutral was given a separate score, resulting in two scores per body part, whereas De Koninck et al. (1992) gave only one score per body part. This might have led to more observed position shifts in the case of this study.

The camera angle/perspective led to the observation from the front view. As a result, e.g. slouching was difficult to observe. However, combining findings from Groenesteijn et al. (2014) and Kamp et al. (2011) with our findings could already give an informative insight.

The use of a 'simple' garden seat design has the advantage that our research outcomes can be applied in multiple transportation industries (e.g. train, car, airplane), but as a disadvantage, the seat might not be as representative. Certain discomfort causes can be traced back to the simplicity of the seat, for instance,

discomfort in the lower back area or the uncomfortable feet/leg support. Future studies should keep this in mind, as Caballero-Bruno et al. (2024) reported that after improving the seat based on a previous study (Caballero-Bruno et al., 2022), the comfort and discomfort experience of the reclined and flat sleeping situation was improved.

The simple seat design that is used, has another disadvantage. The seat pan angle (SPA) was not changed. A different SPA could have helped to improve the comfort feeling of the feet and legs. Stanglemeier et al. (2020) propose the optimal SPA to be 40° backward reclined from a biomechanical perspective. In contrary, this study had a relatively small backward reclined SPA, which might lead to discomfort caused by forward shear forces on the buttock area when the SBA increases, but Wang et al. (2024) found there is a large range of preferences for SPA (between 13° and 30° for a SBA between 110° to 150°). Even though Wang et al. (2024) proved that shear forces are acceptable in a SPA of 13°, the relation between ease of in-seat movement and SPA could further be explored.

### **Limitations and future research recommendations**

This study did not include a diverse age group. Hence, differences between age groups could not be studied. De Koninck et al. (1992) and Skarpsno et al. (2017) reported fewer nocturnal movements during sleep, between older participants compared to younger participants. Also, Skarpsno et al. (2017) reported more side sleeping in older adults, although Vink et al. (2025) did not observe this difference. Age might limit discomfort-triggered adjustments as older adults move less during sleep. Additionally, as the range of motion of joints reduces with age (Soucie et al., 2011), it might become harder to sit in different kinds of seated postures. Milder and Cote (2009) reported an increase in napping frequency with age, which may, in turn, positively impact comfort in upright sleeping positions. Increased daytime sleep experience could facilitate faster sleep onset, as older individuals may be more accustomed to daytime sleep episodes. Future research is needed to examine the effects of age on upright sleeping postures and comfort and to support these hypotheses.

Vibration and movement of the vehicle is reported to play a possible positive and negative role while sleeping (Bouwens et al., 2018; Vink et al., 2025; Vledder et al., 2023). It could be argued that by using a static situation, the comfort experience could be focused on the 'seat' comfort and sleeping postures. However, especially vibration and movement might influence the postures people take during sleep, as they might need to make postural compensations e.g. for cornering movements. Therefore in future research, it should be considered to test in a moving vehicle.

Since the definition of sleeping postures in seats, is a relatively new field, besides the above-mentioned, many other research directions would be beneficial to explore. Previous studies looked at pressure distribution in supine positions in seats (Caballero-Bruno et al., 2022; Stanglmeier et al., 2020). It would be interesting to evaluate the pressure distribution in a seat in the case of lateral trunk postures to identify increased pressure locations. Other related ideas for future research could be: to look into the back sensitivity across the backrest, such as Vink & Lips (2017), but with an increased SBA range; to include cultural sleep habit differences and preferences; and try to link specific sleep postures to sleep quality such as De Koninck et al. (1983) did previously.

## Conclusion

This study examined the impact of seat back angles (SBAs) on sleeping postures and comfort during seated naps, offering insights into the relationships between SBAs, passenger comfort, and discomfort. At upright angles (110°–120°), participants predominantly adopted straight-backed postures with stretched legs, compensating for discomfort through frequent position adjustments. In contrast, reclined angles (150°, 180°) allowed for side-leaning or rotated postures with bent legs and fewer leg crosses, offering greater freedom of movement and significantly reducing discomfort. Comfort levels improved notably between 110° and 140° but plateaued at 140°, 150°, and 180°, highlighting the diminishing returns of a further seat back recline in seated sleeping configurations.

Future seating designs should enhance head and leg support in upright positions while facilitating side-sleeping options in reclined setups to accommodate diverse body types, such as BMI and elbow-to-elbow width variations. These insights are valuable for enhancing passenger sleep comfort in cars, trains, planes, or buses. Additionally, research on pressure distribution in lateral sleeping postures, back sensitivity across a range of angles, and cultural sleep habits can further refine designs.

## Ethical statement

The Human Research Ethics Committee (HREC) of Delft University of Technology approved the study under approval number 2679. All participants provided informed consent and were compensated for their time

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## Conflict of interest

There was no conflict of interest as BMW did not ask for a preferred outcome and the conclusions were made on an independent base.

## Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT to improve the flow and readability of the text. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication

## CRedit Author contributions statement

**Gerbera Vledder:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Visualization, Writing – original draft. **Utkarsh Singh:** Formal analysis, Investigation, Methodology. **Rebeca Sabater Compomanes:** Formal analysis, Visualization, Investigation. **Halil Kılıç:** Resources, Methodology, Investigation. **Maxim Smulders:** Resources, Methodology, Investigation. **Yu Song:** Conceptualization, Formal analysis, methodology, Writing - review and editing. **Peter Vink:** Conceptualization, Methodology, Formal analysis, Writing – review and editing, Project administration, Funding acquisition.

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### 3.3 Human Back Contour Modeling for Backrest Design in Automated Vehicles

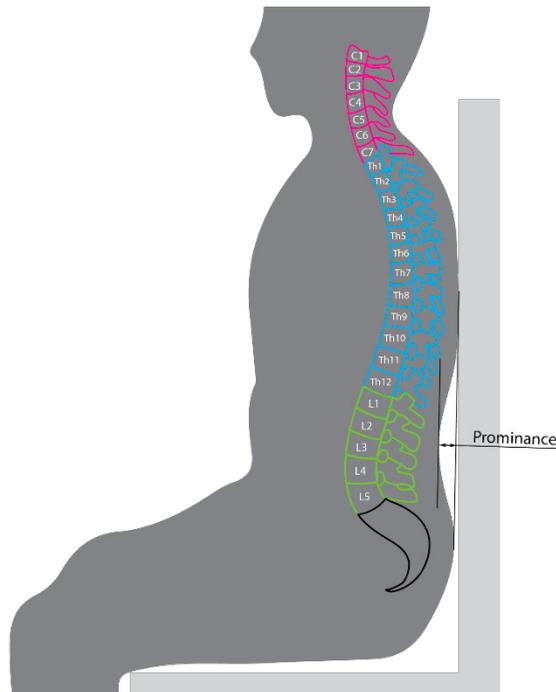
#### Abstract

As automated vehicles evolve, seating designs must accommodate a wider range of postures, particularly for non-driving-related activities like relaxing and sleeping. This study aims to model human back shapes in seated and reclined positions to improve ergonomic seat designs. Human back contour data were collected from 36 participants using a custom measurement device in two setups: a 25° backrest angle and a seat pan angle of 15°, simulating a driving posture, and a 50° backrest angle with the same seat pan angle, representing a reclined posture. Statistical Shape Models (SSMs) were developed to analyze the variability of back contours. The 25° setup exhibited a flatter spinal curve and higher compactness, capturing 79.7% variance with the first principal component (PC1), compared to 74.6% in the 50° setup. The combined setup balanced these differences, offering a comprehensive model for diverse postures. PC1 represents back height, providing a benchmark for determining backrest height and adjustability. PC2 captures neck bending, suggesting the value of a pivotal joint in backrest design to accommodate neck curvature. PC3 highlights lumbar variation, underlining the importance of adjustable lumbar support to suit different lumbar lordosis. These findings offer actionable dimensions for designing ergonomic backrests that support diverse users and postures. Future research should investigate whether implementing these guidelines enhances comfort and should include more diverse populations and a broader range of postures.

## Introduction

The design of automotive seats plays an important role in providing comfort and support during prolonged sitting (Naddeo et al., 2024). The seat contour is often designed to align with the natural shape of the human body. Franz et al (Franz et al., 2011) investigated seat contours in the driver's posture and adapted the backrest and seat pan shapes accordingly, which led to improved comfort. Enlarged contact areas and continuous support along the length of the backrest can help distribute body weight, enhance stability, and reduce pressure concentrations, thereby lowering stress on specific regions and promoting healthy posture (Meakin et al., 2009). However, human body shapes vary, and even for the same individual, different sitting postures can significantly affect the curvature of the lumbar region. For instance, Tsagkaris et al. (Tsagkaris et al., 2022) showed that sitting often flattens the back, decreasing both thoracic kyphosis and lumbar lordosis compared to standing. These variations present challenges to designing backrests that effectively accommodate diverse postures and body types.

The human spine consists of three distinct curves: the cervical (neck), thoracic (upper back), and lumbar (lower back) regions (Kaiser et al., 2024) as shown in Figure 3.3.1. Depending on an individual's sitting height and posture, the thoracic and lumbar regions are most likely to contact the backrest. Studies on spinal angles in upright sitting without a backrest show that the average thoracolumbar angle is approximately  $12.01^\circ$  for males and  $9.76^\circ$  for females, while the lumbar angle is about  $8.8^\circ$  for males and just  $0.28^\circ$  for females (Claus et al., 2016). In other postures, Andersson et al. (Andersson et al., 1979) found that an increase in the backrest-seat angle had only a minor effect on lumbar lordosis. In contrast, Li et al. (Li et al., 2022) observed that thoracic kyphosis angles increased significantly when transitioning from a standing posture to upright sitting and reading/writing positions, while lumbar lordosis decreased substantially or even disappeared. Using MRI techniques, Zemp et al. made measurements on 5 individuals and reported that the mean lumbar, thoracic, and cervical curvature angles were  $29^\circ \pm 15^\circ$ ,  $-29^\circ \pm 4^\circ$ , and  $13^\circ \pm 8^\circ$  in the upright sitting position and  $33^\circ \pm 12^\circ$ ,  $-31^\circ \pm 7^\circ$ , and  $7^\circ \pm 7^\circ$  in a  $25^\circ$  reclined sitting position (Zemp et al., 2013).



**Figure 3.3.1:** The three distinct spinal curves: the cervical (pink), thoracic (blue), and lumbar (green), with the lumbar contour prominence (modified from Kaiser et al. (2024), and M.P. Reed et al. (1995)).

The presence of a backrest, particularly lumbar support, might significantly influence spinal curvature. Andersson et al. (Andersson et al., 1979) found that lumbar lordosis increased proportionally with the addition of lumbar support. A detailed study by Reed and Schneider (Reed and Schneider 1996) reported that, with a fixed backrest angle of 20° and flexible lumbar support adjustable up to 120 mm above seat pan (Reed, Schneider, and Eby 1995), the lumbar contour prominence measured approximately  $1.5 \pm 5.8$  mm without support and  $10.9 \pm 9.0$  mm with a 40 mm high lumbar support in preferred driving postures. However, the position of the lumbar support along the backrest was not specified. Regarding the height of lumbar support, Carcone and Keir (Carcone & Keir, 2007) demonstrated that a 3 cm lumbar pad effectively provided support and prevented flattening in the lumbar area, underscoring the importance of lumbar support for maintaining comfort during sitting.

In a well-designed seat, the trunk is supported by the backrest, allowing the muscles to relax and the lumbar contour prominence in the form of lordosis (in the sagittal plane) to maintain its natural curve (Varela et al., 2019). While substantial effort has been devoted to understanding differences between and within individuals across various postures, significant gaps remain: 1) Most

studies have primarily focused on upright sitting and standard driving postures, such as backrests fixed at a 20° angle, leaving other postures insufficiently explored. This gap becomes particularly relevant with the development of automated vehicles, where non-driving-related activities (NDRAs) (Cai et al., 2024), especially sleeping (P. Vink et al. 2025), are becoming increasingly prominent; 2) In seated postures, the back aligns from the buttocks upward, and variations in sitting height complicate the use of angular spinal measurements for backrest design. Moreover, there is a lack of comprehensive geometric models that can accurately represent the human back contour, particularly in seated and reclined positions. Addressing these gaps is essential for advancing backrest designs that can effectively support a wide range of postures and activities in automated vehicles.

This paper is an attempt to address these gaps by exploring two research questions: (1) What is the model of human back shape in seated positions? (2) Is it possible to incorporate more postures, such as sleeping, into the model to better accommodate NDRAs in automated vehicles? By addressing these questions, this study aims to establish a foundation for understanding human back contours across various seating postures and to support the development of adaptable backrest designs that improve comfort across a broad range of in-vehicle activities in the context of emerging automated mobility.

## Materials & Methods

### Experiment setup

An experiment was conducted at the Comfort Lab of Delft University of Technology to investigate human back contour measurements. A digital measurement device, named the Digital Kyphometer, was specifically developed for this purpose, as shown in Figure 3.3.2 (a). The device features a probe mounted on a vertical linear track, enabling it to record both horizontal and vertical movements of a wheel at the end of the probe as it moves along the track. Compared to other measurement methods (de Oliveira et al. 2012; Voinea, Butnariu, and Mogan 2016; Kandasamy, Bettany-Saltikov, and van Schaik 2021; Nijholt et al. 2016), the Digital Kyphometer offers a faster and more efficient way to digitize vertical back profiles.

In addition, a custom wooden seat was fabricated with a 15° seat pan angle and adjustable backrest angles of 25° and 50°. The dimensions of this setup are illustrated in Figure 3.3.2 (b). The 25° backrest angle was selected as it is the most commonly observed angle among drivers (Reed et al. 2020). In contrast, the 50° backrest angle was chosen based on recent studies suggesting that it provides comfort for sleeping (Vledder et al. 2024). A distinctive feature

of the seat is the U-shaped slot at the center of the backrest, which allows the probe direct access to the back during measurement. Two layers of foam, totaling 6 cm in thickness, were placed on the seat cushion. The distance from the bottom of the U-shaped slot to the top of the foam is approximately 7 cm, measured along the direction of the backrest. The 7 cm clearance was reserved to ensure that the probe could move freely while accessing the back contour of the participants during measurement. Figure 3.3.2 (c) shows an experiment session, during which the wooden seat was positioned on a table to align with the measurement range of the device. The device was placed behind the seat at an  $11^\circ$  inclination relative to the ground plane, allowing improved access and more accurate back contour measurement.

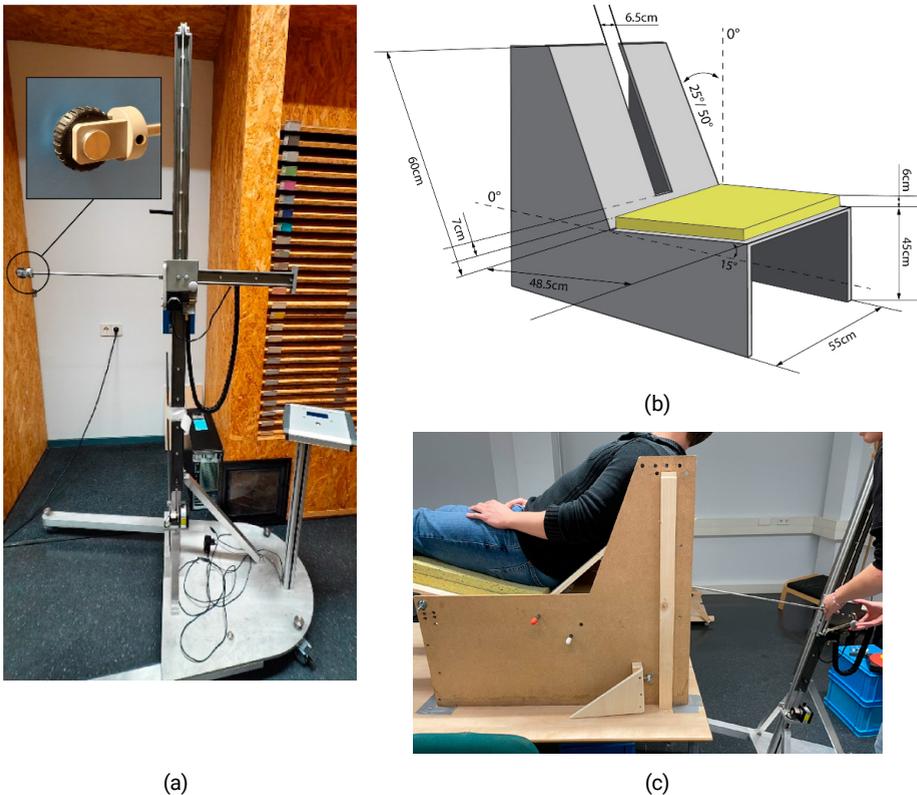


Figure 3.3.2: Experiment setup, (a) The Digital Kyphometer used for back contour measurement with a detailed view of the wheel at the end of the probe; (b) the Dimensions of the custom experimental seat with a U-shaped slot allowing access for the kyphometer probe; (c) a participant seated during measurement.

### Participant

The participants consist of 18 males, 17 females, and 1 other gender. The majority (30 participants) are of Western European origin, primarily Dutch

nationals. The group also includes individuals from South and Southeast Asia (3), East and Central Asia (1), Eastern Europe (1), and North Africa (1), reflecting a limited ethnic diversity. Table 3.3.1 presents the participants' anthropometric data. Figure 3.3.3 shows the distribution of participants based on stature and hip width. The shaded ellipse represents the range between the 5th percentile (P5) and 95th percentile (P95) of the Dutch population for both dimensions, encompassing the central portion of the sample (Dined, 2011).

Table 3.3.1: Anthropometry of the participants

|                          | Mean±STD  | Min   | Max  |
|--------------------------|-----------|-------|------|
| Age                      | 26.4±10.2 | 19    | 66   |
| Stature height (CM)      | 174.7±8.7 | 158.1 | 191  |
| Popliteal height (CM)    | 47.2±3.2  | 41.6  | 53   |
| Buttock-knee height (CM) | 50.1±2.4  | 45.8  | 55   |
| Sitting height (CM)      | 89.7±4.1  | 80.7  | 97.5 |
| Hip width (CM)           | 38.5±3.4  | 33.4  | 48   |
| Weight (Kg)              | 71.5±13.5 | 48    | 98   |

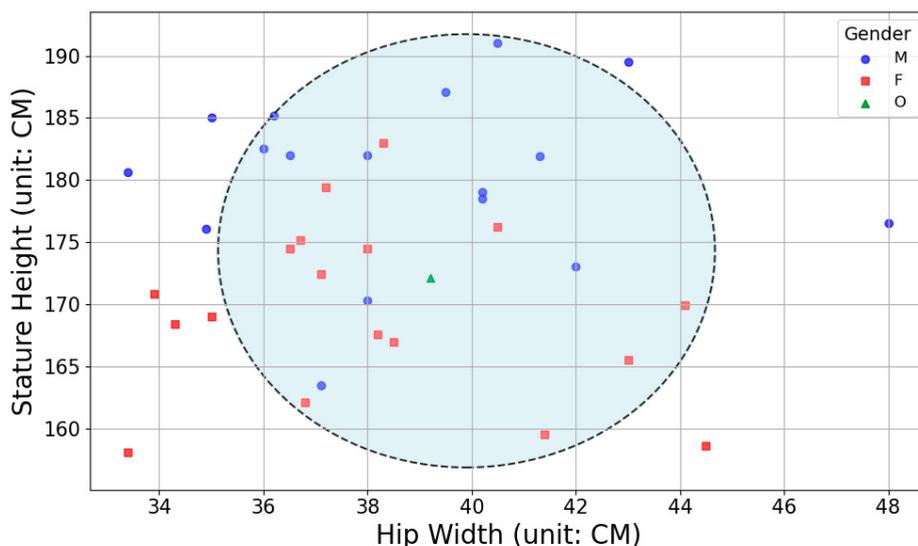


Figure 3.3.3: Distribution of stature and hip width of participants

### Protocols

Informed consent was obtained from all participants prior to the study. Anthropometric measurements were collected using a measuring chair to document the participants' physical dimensions following the procedure

described by Molenbroek et al. (Molenbroek et al., 2017). Subsequently, the kyphometer and the corresponding wooden seat were adjusted to the appropriate settings based on the specified backrest angles, the origin of the kyphometer measurement was aligned with the top surface of the foam pad, and the probe was placed perpendicular to the seat backrest in the U slot. At the 25-degree backrest angle, participants were instructed to look at a fixed point in front of him/her to simulate a driving posture. At the 50-degree backrest angle, no instructions were given for the head position. Additionally, the angle of the hip is defined by the seatpan and backrest position. The researcher then used the kyphometer to measure the back contour, starting from the seventh cervical vertebra (C7), (Wiyad et al., 2023) moving the probe wheel along the spine to the bottom of the U slot, recording data at approximately 1 cm intervals. Making one recording took approximately 3 seconds. The digital kyphometer was manually moved in the vertical direction with a spring mechanism and manual constant pressure to the end of the probe assuring contact to the participants spine in the horizontal direction. This process was repeated three times directly after each other to ensure consistency and reliability to compensate in differences in vertical movement speed. For the 50-degree backrest angle measurement, participants were instructed to relax as much as possible while seated, and the contour measurement process was repeated under these conditions. The head position was left unrestrained, as occupants tend to vary their head posture while sleeping or relaxing.

### Data processing

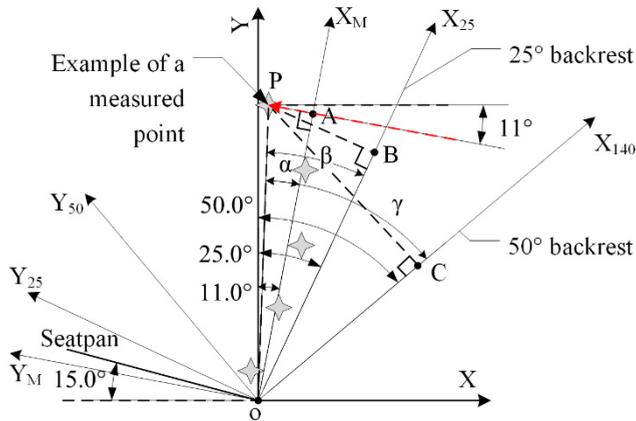
All collected data were documented. Given a set of measured points of a contour of the human back, the acquired data can be represented as

$$P_{C_M}^{s,i,m} = \left\{ p_{C_M}^{s,j,m,i} \mid i = 0 \dots n^{s,j,m} \right\}$$

where  $p_{C_M}^{s,j,m,i}$  represents the  $i_{th}$  measured point of the  $j_{th}$  subject in the  $m_{th}$  try in the measurement coordinate system  $C_M (X_M O Y_M)$  for the  $s_{th}$  setup, and  $n^{s,j,m}$  is the number of points in the pointset  $P_{C_M}^{s,i,m}$ . Here  $S = [25, 50]$ , referring to the 25° and 50° setups, respectively. An example of  $p_{C_M}^{s,j,m,i}$  is the point  $P$  in Figure 3.3.4, and the x and y coordinate of  $P$  is  $[OA, PA]$  in  $C_m$ .

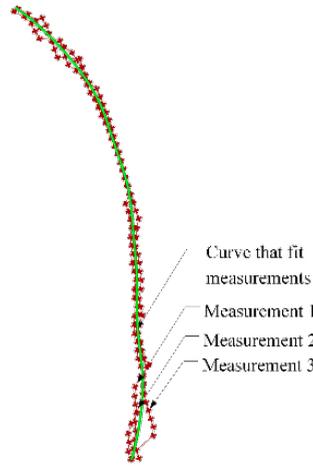
As the measurement was conducted in 25° and 50° backrest angles, the distances between point  $P$  and each backrest have more meaning regarding the shape of the human back contour. Therefore, two coordinate systems  $C_{25} (X_{25} O Y_{25})$  and  $C_{50} (X_{50} O Y_{50})$  based on two backrests were established as Figure 4. The X and Y coordinates of point  $P$  in  $C_{25}$  can be represented as  $[OB, PB]$ . Here the x-coordinate  $OB = PO \cos(\beta)$ , and the y-coordinate is

computed as  $PB = PO \sin(\beta)$ , where  $PO = \sqrt{PA^2 + OA^2}$ ,  $\beta = 14 + \alpha$ , and  $\alpha = \tan^{-1}PA/OA$ . In  $C_{140}$ ,  $P$  is represented as  $[OC, PC]$ . Here  $OC = PO \cos(\gamma)$ , where  $\gamma = 39 + \alpha$ , and  $PC = PO \sin(\gamma)$ .

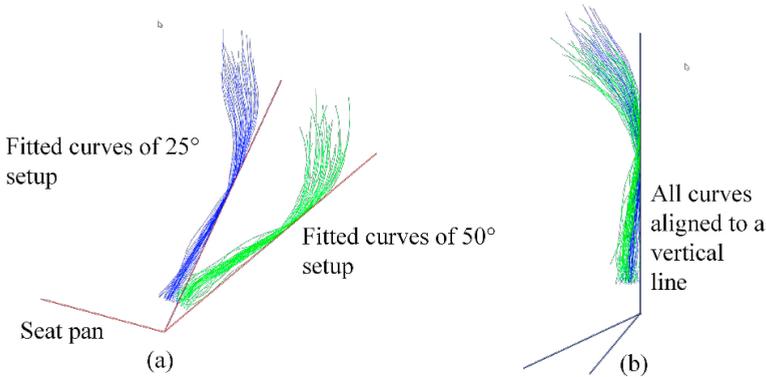


**Figure 3.3.4: Correction of measurement results- X – X-axis of World coordinate system; XM - X-axis of  $C_m$ ; X25 - X-axis of  $C_m$ ; X50 – X-axis of  $C_{50}$**

For each subject in each setup ( $s = 0$  for  $25^\circ$  and  $s = 1$  for  $50^\circ$  setup),  $m = 3$  times the measurements were conducted, respectively. All measured points were translated to the corresponding coordinate system following the methods above. Then 3-degree splines were used to fit the results (Figure 3.3.5), resulting in two sets of non-uniform rational b-spline (NURBS) curves  $SP^s = \{SP^{s,j}(u) | u \in (0,1), s = [25,50], j = 1..36\}$  for each participant in each setup, where  $u$  is the normalized parameter of the curve. Figure 3.3.6(a) presents two sets of these curves. In Figure 3.3.6(b), we aligned the X-axis of  $C_{25}$  and  $C_{50}$  to Y-axis of the world coordinate (XOY) for a better comparison of two set of curves.



**Figure 3.3.5: Fitting 3 sets of measurement points with a 3-degree B-Spline curve for one participant**



**Figure 3.3.6: (a) The interpolated curves in 25°(blue) and 50° (green) setups, (b) all curves aligned to a vertical line for analysis**

Given a set of 36 curves  $SP^{25} = \{SP^{25,j}(u) | u \in (0,1), j = 1..36\}$  for the 25° setup, each can be discretized to a set of points as  $SP_D^{25} = [SP^{25,j}[i], i = [0,1,2\dots n], j = 1..36]$ , where  $n$  is the number of points. A statistical shape model (SSM) of  $SP_D^{25}$  can be built based on principal component analysis (PCA) (Yang et al., 2021) as:

$$SP_{ssm}^{25} = SP_{Dmean}^{25} + \sum \gamma_k^{25} PC_k^{25}.$$

Here  $SP_{Dmean}^{25}$  denotes the mean model of  $SP_D^{25}$ .  $\gamma_k$  are the coefficients of  $PC_k$ , which are a number of uncorrelated principal components (PCs). Similarly,  $SP_{ssm}^{50}$ , which is the SSM of  $SP_D^{50}$ , and  $SP_{ssm}$ , which is the SSM of all curves in both 25° and 50° setups, can be denoted as:

$$SP_{ssm}^{50} = SP_{Dmean}^{50} + \sum_{k=0}^{q50} \gamma_k^{50} PC_k^{50}$$

and

$$SP_{ssm} = SP_{Dmean} + \sum_{k=0}^q \gamma_k PC_k.$$

## Results

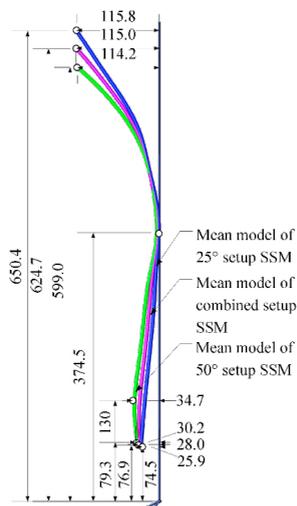
Figure 3.3.7 illustrates the mean models of the three SSMs for the 25° setup, 50° setup, and the combined setup. These mean models represent the average human back contours derived from the SSMs, highlighting variations in back curvature across different backrest angles. In the mean model, the 50° setup demonstrates a more pronounced curvature, indicative of a relaxed and reclined posture, while the 25° setup shows a flatter curvature, consistent with an upright driving posture. The combined setup balances these two configurations, capturing the diversity in back shapes across both backrest angles.

For the top positions of the mean models, the 25° setup has a prominence of 115.8 mm from the backrest and 650.4 mm to the foam surface of the backrest. The 50° setup has a prominence of 114.2 mm from the backrest and 599.0 mm to the bottom of the backrest. The combined mean model lies in between, with a prominence of 115.0 mm from the backrest and 624.7 mm to the bottom of the backrest.

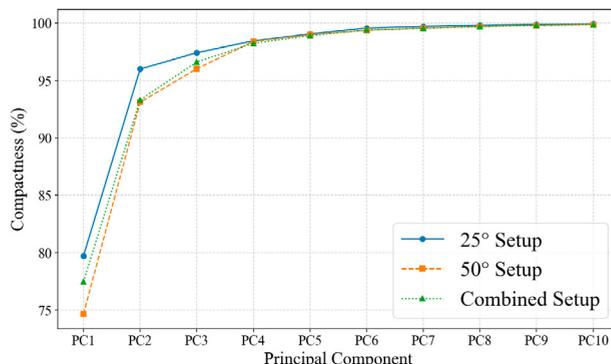
In the 50° setup, the prominence in the lumbar lordosis region reaches a maximum of 34.7 mm, positioned 130 mm above the seat pan level. At the same level above the seat pan, the prominence in the lumbar lordosis region of the combined setup and 25° setup are 28.0 mm and 21.3 mm, respectively. At 374.5 mm above the seat pan level, the prominence of the three curves regarding the backrest are the smallest.

Figure 3.3.8 presents the compactness of the three SSMs, detailing the variance captured from PC1 to PC10 for each setup. The 25° setup consistently demonstrates the highest compactness across the components, capturing 79.7% of the variance in PC1, 97.42% by PC3, 99.06% by PC5, and over 99.95% by PC10, indicating that fewer components are required to represent the shape effectively. The 50° setup initially captures less variance, with 74.6% in PC1, 96.02% by PC3, 98.99% by PC5, but converges to similar compactness levels (over 99.95% by PC10). The combined setup balances the compactness of both individual setups, capturing 77.5% in PC1, 96.61% by PC3, 98.92% by PC5, and over 99.95% by PC10, suggesting that while it accommodates greater diversity,

it retains reasonable compactness. These compactness trends highlight that the 25° setup yields the most compact representation of back shapes, likely due to the lower inter-subject variability typically observed in driving postures compared to the more relaxed and variable 50° setup, which will be further discussed in Section 4.2.



**Figure 3.3.7: Mean model of the 25°, 50° and combined setups, distance unit in mm**

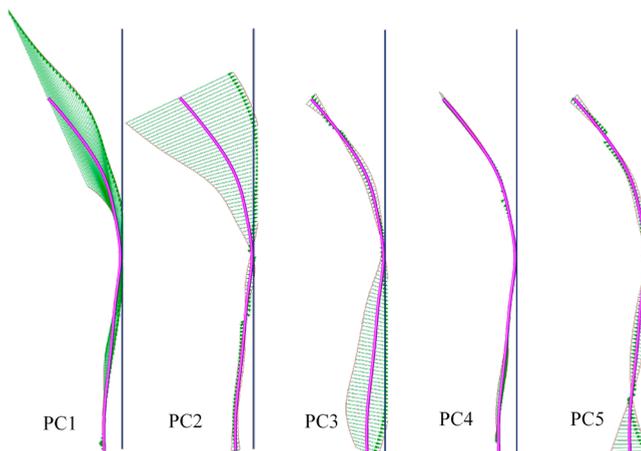


**Figure 3.3.8: Compactness of the model**

To further understand the pronounced curvature in the 50° setup compared to the 25° setup, we discretized the interpolated curves into 100 points to evaluate the accuracy of the mean models, as shown in Table 3.3.2. The mean direct Hausdorff distance, its standard deviation (std), and the Root Mean Square Error (RMSE) were calculated for each setup (Song et al., 2005). The 25° setup exhibited the lowest mean error ( $5.01 \pm 4.95$  mm) and RMSE (7.04 mm), reflecting a high degree of accuracy and consistency in representing the back shapes. In contrast, the 50° setup showed significantly higher errors, with a mean error of  $15.73 \pm 13.44$  mm and an RMSE of 20.70 mm, likely influenced by the variability in relaxed postures adopted by participants. The combined setup achieved a mean error of  $6.28 \pm 7.66$  mm and an RMSE of 9.91 mm, balancing the errors from both individual setups.

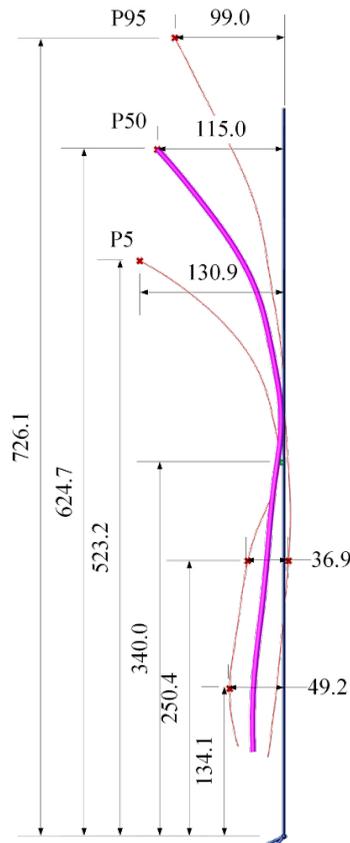
Table 3.3.2: Errors from the interpolated curves to the mean model

|                | Mean error (mm) | RMSE  |
|----------------|-----------------|-------|
| 25° setup      | 5.01±4.95       | 7.04  |
| 50° setup      | 15.73±13.44     | 20.70 |
| Combined setup | 6.28±7.66       | 9.91  |



**Figure 3.3.9: The combined SSM illustrating the mean human back contour along with the range of variability represented by  $\pm 3$  STD**

Figure 3.3.9 presents the combined SSM along with the range of variability from PC1 to PC5, represented by  $\pm 3$  standard deviations (STD), which account for 0.135% to 99.862% of the total shape variation for each principal component. In this model, PC1 primarily influences back height, PC2 captures variations in neck bending, and PC3 reflects differences in the lumbar lordosis region. For PC4 and PC5, the variations are smaller and less visually pronounced, indicating diminishing contributions to overall shape diversity.



**Figure 3.3.10: Dimensions of the P5 to P95 human back contours generated by the model (in mm)**

Figure 3.3.10 presents the dimensions of the P5 to P95 back curves ( $\pm 1.645$  SD) based on PC1, PC2, and PC3. The sitting height in these curves ranges from 523.2 mm to approximately 726.1 mm, measured from the seat pan level. The maximum prominence difference in the lumbar lordosis region between P5 and P95 is 49.2 mm, located 134.1 mm above the seat pan. It is noteworthy that this prominence difference remains 36.9 mm even at a height of 250.4 mm above the seat pan, indicating consistent variability further up the back.

## Discussion

This study addressed two research questions: (1) What is the model of human back contour shapes in seated positions? (2) Can the model be extended to incorporate additional postures, such as sleeping, to better accommodate non-driving-related activities (NDRAs) in automated vehicles? By developing SSMs

and analyzing key shape parameters and their variations, this study presents new insights into human back contours in both seated and reclined postures.

### **The SSM model**

The SSMs generated in this study provide detailed geometric insights into back shapes across different postures. For the distance from C7 to the seat pan, the 25° setup measures 650.4 mm, the combined setup measures 624.7 mm, and the 50° setup measures 599.0 mm above the seat pan level in the mean models. The 50° setup is only slightly higher than the average sitting height (598 mm) in the Dutch population (Dined, 2011). However, C7 is generally positioned higher than the shoulder in the seated posture. This discrepancy might be due to: 1) In standard sitting height measurements, the seat pan angle is 0° and the backrest is vertical, with participants instructed to sit in an upright posture (Molenbroek et al., 2017). In contrast, in this study, the seat pan angle was 15°, and the backrest angle was either 25° (driving posture) or 50° (relaxed, reclined posture); 2) In this experiment, participants sat on a 6 cm thick foam cushion, and the resulting deformation was not accounted for. In contrast, anthropometric measurements are typically conducted with participants seated on a rigid wooden surface; and 3) The differences between the rotation centers of the participant's body and the seat backrest also contributed to discrepancies in the measured back contour.

In all setups, the prominence of C7 regarding the backrest remains consistent at approximately 115 mm, aligning with values reported in existing literature. For instance, Kim et al. (Kim et al., 2015) noted that the preferred pillow height for supporting the cervical region in reclining postures was approximately 10 cm, which closely corresponds to this measurement.

PCs in the SSMs reveal significant shape variations. PC1 primarily reflects the overall height of the human back contours, representing the largest source of variability across the population. PC2 captures the bending of the cervical spine, highlighting differences in alignment among participants. PC3, on the other hand, shows the greatest variation in the lumbar region, particularly in areas influenced by lumbar support. These findings emphasize how back contour variability is distributed across height, the thoracic area, and the lumbar regions, providing critical insights for specifying different dimensions in backrest design to enhance support and comfort.

### **Human back contours in Seated Postures**

The results highlight the substantial differences in human back curvature between the 25° and 50° backrest setups. The mean models indicate that the 25° setup produces a flatter back contour, consistent with the upright posture typically associated with driving. In contrast, the 50° setup exhibits

larger variations among all curves and generates a more pronounced back curvature, a finding that contrasts with previous literature (Andersson et al., 1979; Li et al., 2022). Specifically, the mean error of the SSM for the 50° setup is 15.73 mm, more than three times higher than the 5.01 mm observed in the 25° setup. The compactness analysis further supports these findings: the 25° setup demonstrates higher compactness, capturing 79.7% of the variance in PC1, compared to 74.6% in the 50° setup.

During the experiment, the absence of a fixed task in the 50° (relaxed) condition allowed participants to adopt a wider range of natural postural behaviors, likely contributing to the greater variability observed. This reinforces the conclusion that human back contours in driving postures are relatively consistent, while those in relaxed positions are inherently more diverse. These insights underscore the importance of designing backrests that can adapt to a broader spectrum of user preferences and activities, particularly in automated vehicles, to ensure both stability and comfort across varied postures.

## **Design implications**

### *Backrest height*

PC1 of the model indicates that the principal variation lies in the height of the back contour, making it a key consideration for backrest design. The dimensions of the P5 to P95 back curves provide actionable benchmarks, particularly for backrest height and adjustability. Figure 3.3.10 suggests that the minimum height from C7 to the seat pan should be approximately 523.2 mm for the P5 population. This is consistent with findings in the literature (Nijholt et al. 2016), which emphasize that participant back shapes vary significantly from the commonly assumed 440 mm vertical distance from the seat pan.

Headrest adjustability becomes even more critical when accommodating a diverse population. To support users ranging from the P5 to P95 percentiles, the headrest must offer 202.9 mm of vertical adjustment to ensure proper head and neck support. This range enables optimal positioning for both shorter and taller individuals across different activities, such as relaxing or sleeping in automated vehicles.

### Possible hinge joint in the backrest

PC2 of the model reveals that the second-largest variation lies in the bending of the neck. Using the mean model for backrest design may result in a compromise in this area, as it does not fully accommodate the variability in neck curvature across individuals. An alternative approach could be to introduce a hinge joint at [0, 374.5] as shown in Figure 3.3.7, allowing the backrest to adapt dynamically to these variations and better support different neck alignments. This adaptive feature could enhance user comfort, particularly for different NDRAs.

A three-vertex polyline, denoted as (PP1, PP2, PP3), was defined as illustrated in Figure 3.3.11. This polyline was constructed within the bounding box of the target curves. One vertex (PP1) was placed on the top edge of the bounding box (as a parameter), another vertex (PP3) was located on the bottom edge (also as a parameter), and the third vertex (PP2, the hinge joint) was defined as [0, 374.5].

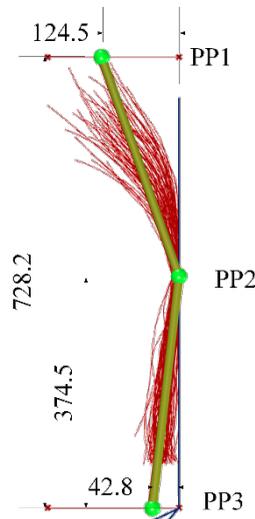


Figure 3.3.11: The fitted polylines (units: mm)

The best-fit polylines PP(PP1, PP2, PP3) were determined for the combined setup, where PP1 and PP3 were identified by minimizing the sum of squared distances between the polyline and each point in the relevant back curves  $P_{C_M}^{s,i,m}$ . This optimization problem is represented mathematically as:

$$PP(PP1, PP2, PP3) = \arg \min_{PP1, PP3} \sum_{j=0}^{72} \sum_{k=0}^n D(PP, P_{C_M}^{s,i,m})^2$$

where  $D$  is the Hausdorff distance calculated between PP and the  $n$  discretized back curves  $P_{CM}^{s,i,m}$ . The results of this fitting are presented in Figure 3.3.11, showing the dimensions of PP1, PP2, and PP3 with an RMSE of 17.73 mm.

### *Lumbar support*

The third-largest variation in the model (PC3) is located in the lumbar region. To support the P5 to P95 population, a lumbar support with an adjustable height of up to approximately 49.2 mm, positioned 134.1 mm above the seat pan level, is necessary. Additionally, this support must accommodate a broader vertical range. Specifically, it may need to extend as high as 250.4 mm above the seat pan, while still providing a support height of 36.9 mm at that level, as shown in Figure 3.3.9. This finding is consistent with the literature: for instance, Korte (Korte, 2013) recommended a lumbar support height of  $192 \pm 31$  mm for office chairs. Carcone and Keir (Carcone & Keir, 2007) also reported a 3 cm support height for office seats. Furthermore, the vertical positioning of the lumbar support in this study, extending downward toward the seat pan, is consistent with the 120 mm coverage suggested by Reed et al. (Reed, Schneider, and Eby 1995), reinforcing its relevance to vehicle seat design.

### **Limitations and Future Directions**

While this study advances our understanding of back shapes in seated positions, several limitations must be acknowledged. First, although the participant sample included a range of individuals, it was predominantly of young Western European origin. This may limit the generalizability of the findings to other populations with different anthropometric characteristics. For instance, the curvature of the cervicothoracic spine changes progressively with age (Boyle et al., 2002). Future studies should aim to include a more ethnically and geographically diverse sample to better capture the full spectrum of back contour variability. Furthermore, though we attempted to balance gender during recruitment, the limited number of participants prevents us from reporting differences among genders.

Additionally, this study focused solely on two static seated positions representing typical driving and relaxing/sleeping postures. While these postures provide valuable insights into back contours at specific backrest angles, there are further considerations: 1) The notion of an “ideal” sitting posture is still debated (Claus et al., 2009). The comfortable postures identified in the 50° setup were based on participants’ subjective preferences, which can vary significantly depending on the activity; 2) Dynamic measurements during transitions between postures could offer a more comprehensive understanding of how back contours evolve over time. Such transitions are important, as spinal curvature is known to adapt in response to changing postures.

The restricted range of backrest angles, limited to 25° and 50°, also constrains the scope of the findings. Including a broader spectrum of angles could improve the adaptability of the SSM, making it applicable to a wider variety of postures and activities, particularly in automated vehicle scenarios. In addition, the use of a flat, neutral backrest is another limitation. Since back contours vary with backrest design (e.g., contouring, flexibility, tilt), no single configuration can be considered representative (Tsagkaris et al. 2022). We therefore selected a neutral flat backrest to minimize design-specific effects and focus on body back contour variability.

The absence of a headrest in the setup is another limitation. Headrests can alter cervical alignment and load distribution, especially in reclined postures (Reed and Schneider 1996). Their absence, particularly in the 50° condition simulating sleeping postures, may have contributed to participants' difficulty in achieving comfort and to the greater variability observed in cervical back contours. However, the headrest was intentionally excluded to avoid introducing design-specific influences and to capture the intrinsic variability of back shapes without constraining participants to a particular headrest geometry. This choice led to greater variation in PC1 of the 50° setup (cervical area), but this variation also highlights the naturally diverse postures adopted by participants.

Meanwhile, a 7 cm offset from the seat pan meant the buttock region was not fully captured. Although the dataset includes the neck, shoulder, and lumbar areas, the role of buttock shape, potentially influencing PC3 and PC5, remains uncertain and warrants further study.

Lastly, the theoretical findings presented in this study should be evaluated in practical applications. Designing a seat that follows the back contour as described here is recommended, and it would be valuable to assess whether participants perceive such a seat as more comfortable or experience reduced discomfort compared to traditional designs.

## Conclusion

This study advances the understanding of human back contour shapes in seated and reclined positions through the development of SSMs. The findings reveal that the 25° backrest setup produces a flatter back contour, while the 50° setup shows greater variability and a more pronounced curvature. The combined setup balances these differences, offering a comprehensive model for diverse activities. Future research should include a more demographically diverse population and investigate the influence of headrests on back contour

and perceived comfort, especially in reclined postures relevant to automated vehicles.

### **Ethical statement**

The present research was approved by the Human Research Ethics Committee (HREC) of Delft University of Technology under file number 4717. Informed consent was obtained from all participants prior to their involvement in the study.

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CHAPTER

# 4

# PRODUCT CHARACTERISTICS

The following chapter builds on the findings from the previous chapters and sections. As could also be seen in Figure 1.3, the environment, the person, the product characteristics, and Usage/Task are intertwined. In this chapter, the focus will be on how the product characteristics and the Usage/Task influence the formation of comfort and discomfort while also paying attention to the other factors in the process.

In section 2.1, it was found that noise has a large impact on the formation of discomfort in turboprop airplanes. In section 4.1, the effectiveness of earplugs and noise-cancelling headphones to improve the acoustic comfort in turboprop airplanes is tested. With the input of the previous findings on sleeping environments during transit, several day and night train interiors were designed. In section 4.2, these day and night train interiors are evaluated, specifically exploring the impact of privacy and security on comfort.

This chapter is based on the following articles:

1. Vledder, G., Yao, X., Song, Y., & Vink, P. (2025). Effectiveness of earplugs and noise cancelling headphones to improve turboprop acoustic comfort. *WORK: A Journal of Prevention, Assessment and Rehabilitation*. <https://doi.org/10.1177/10519815251333749>
2. Out, A., Vledder, G., Vink, P. Towards a more efficient train use: A VR case study evaluating a comfortable night/day train design. *International Comfort Congress 2025*.

## 4.1 Effectiveness of earplugs and noise cancelling headphones to improve turboprop acoustic comfort.

### Abstract

**Background:** Current jet airplanes are not sustainable, and turboprop aircraft can be a more sustainable alternative for regional travels. However, the noise levels in turboprops can range from 83 to 92 dB(A), which is higher than jets and is the largest contributor to discomfort in turboprops.

**Objective:** The objective of this study was to assess the efficacy of utilizing noise-cancelling headphones or earplugs in mitigating (dis)comfort experienced by passengers aboard turboprop aircraft.

**Methods:** An experiment was designed in a grounded Boeing 737 cabin with the sound source inside. Twenty-four participants experienced four conditions: jet sound (Boeing 737), turboprop (ATR 72) sound, turboprop sound with active noise-cancelling (ANC) headphones, and turboprop sound with earplugs. The sound level used for all conditions in this test ranged between 84.2 and 86.3dB(A). Passenger experiences were measured using questionnaires, including a newly developed Ear Local Discomfort questionnaire.

**Results:** The comfort and discomfort scores for the conditions involving ANC headphones and earplugs are significantly improved compared to the conditions without hearing protection. The impact of noise on discomfort is mitigated in these two conditions, though it remains the most prominent factor. ANC headphones cause more discomfort around the ear, while earplugs cause discomfort inside the ear.

**Conclusion:** The use of ANC headphones and earplugs in a turboprop airplane might increase the acceptance of these airplanes. ANC headphones are slightly preferred over earplugs, but both solutions have specific limitations.

## Introduction

Turboprop airplanes can play an important role in enabling an all-electric aircraft system with almost no emissions (Schäfer et al., 2018). Even in their current configuration turboprops consume 10-60% less fuel compared to regional jet flights (Babikian et al., 2002). However, the noise levels in turboprops are relatively high, ranging from 83 to 92 dB(A) depending on the seat location in the aircraft, flight phase, and aircraft type (Zevitas et al., 2018).

Noise might reduce the total comfort and increase the discomfort of passengers. A good comfort rating is related to passengers' willingness to fly with a certain airline (Vink et al., 2012). According to Bouwens (2018), comfort in a jet engine airplane is dependent on the seat, noise, light, temperature, vibrations, and smell, in descending order of importance. Vink et al. (2022) found that noise is the largest contributor to discomfort in a turboprop aircraft.

Auditory comfort is a complex notion integrating subject-related factors (e.g. noise sensitivity, prior experience), situational factors (e.g. context, the task at hand), and physical factors (Valentin et al., 2022). Quehl et al. (2001) connected auditory comfort to the absence of annoyance. Technically there is no difference between sound and noise, although the distinction is relevant for the human listener (Berglund & Lindvall, 1995). "Noise is unwanted sound, or more precisely: noise is unwanted sound given one's current needs, goals, and activities." (Andringa & Lanser, 2013). Therefore it is difficult to define noise by amplitude or frequency as it might be different for everyone, and is depending on the activity. Sounds with prominent tones (Quehl et al., 2001) and fluctuations in pitch are often very annoying (Soeta & Shimokura, 2013). Additionally, the influence of low-frequency noises (10Hz to 200Hz) on annoyance is often underestimated (Leventhall, 2004).

Fink (2019) emphasizes the harmful effects noise can have on people and animals. Noise exposure can have a direct influence on people by inducing hearing loss, when exposed to high sound levels, and can have an indirect effect (non-auditory effects) which manifests in annoyance, and disturbance of e.g. concentration, relaxation, or sleep (Babisch, 2002). Sound pressure levels (SPL) are often used to define the amplitude of the noise. Sleep is disrupted at 30 dB(A) and concentration at 45 dB(A) (Fink, 2019). The threshold for physical discomfort (loudness discomfort level) is in the range of 80-100 dB SPL (Berglund & Lindvall, 1995). Occupational safety regulations restrict the noise exposure to be maximally 85 decibels averaged over 8 working hours, measured as a time-weighted average (TWA)(OSHA, n.d.). Above 85dB(A) employees are obliged to wear hearing protection (European Commission, 2003). Regarding

the frequency, interior noise in turboprop airplanes is attributed to a dominant tonal component in the low-frequency band, in the case of an ATR 72-500 around 100 Hz (Müller et al., 2022) which is generated by the blade passage frequency (Yoon et al., 2019).

Passive hearing protection nor active noise cancelling (ANC) headphones are new inventions, with the latter being developed by the U.S. Air Force more than 50 years ago (Stephenson, 2009). Hearing protection exists in the form of earmuffs or earplugs, both with options for active or passive hearing protection. Certain product families for external-ear worn products can be defined as over-the-ear headphones, around-the-ear headphones, in-the-ear headsets, behind-the-ear headsets, and in-the-ear headsets with ear hooks (Stavarakos et al., 2015).

Passive hearing protection reduces noise and filters frequencies by using noise-blocking materials, while active hearing protection cancels out noise by generating sound waves that precisely match and reverse the frequency and amplitude of the incoming noise (Guldenschuh et al., 2012). Where passive hearing protection works best in attenuating high-frequency noises (>500Hz) (Ang et al., 2017), ANC systems are very efficient in attenuating low-frequency noises (Kajikawa et al., 2012). For instance, a motor helmet with ANC can effectively reduce motorcycle engine noise by 40 dB in the range <200Hz, and by 15 dB between 200 to 600 Hz (Kajikawa et al., 2012). Though the performance of ANC varies among different types of products (Ang et al., 2017), earplugs and ANC headphones need to meet the standard of a minimal noise reduction of 12, 11, and 9 dB(A) for compliance (CEN, 2020a, 2020b).

While controlling noise levels with earplugs may enhance the comfort of passengers in jet engine airplanes (Bouwens et al., 2021), it also presents challenges related to comfort, convenience, cost, communication, and corporate culture and safety (Stephenson, 2009). For instance, prolonged use of headphones may lead to discomfort around the ears. When evaluating the comfort of earplugs, people first consider if the earplugs cause physical discomfort, followed by the functional fit and effectiveness, the satisfaction and well-being, and the acoustical attributes (e.g. intelligibility of alarm signals, and discomfort due to internal noises) (Valentin et al., 2024).

The study's objective is to assess the effectiveness of various noise cancellation methods in turboprop flights in terms of passenger comfort. This inquiry leads to the research question: What is the impact of using noise-canceling headphones or earplugs on passenger comfort and discomfort in turboprop airplanes?

## Materials & Methods

### Participants

Twenty-four participants with prior air travel experience were recruited, although not all of them had experience with turboprops (Experience: 37.5%, No experience: 16.7%, Uncertain: 45.8%). Participants with self-reported hearing impairments were excluded from the study. The sample size of twenty-four participants was determined based on a power analysis conducted prior to the study (power = .95, alpha = .05, effect size = .8), comparing the means of two dependent groups using non-parametric tests in a two-tailed setup. Table 4.1.1 displays the participants' demographics. Anthropometric measurements were recorded following the procedure by Molenbroek et al. (2017). Two participants did not fill out all questions for unknown reasons.

Table 4.1.1: Participant details and anthropometric measurements

|                              |                   |
|------------------------------|-------------------|
| Total number                 | 24                |
| Age                          | 27±4.016          |
| Sex                          | 12 Male/12 Female |
| Stature (mm)                 | 1684±85.675       |
| Mass (kg)                    | 69±16.159         |
| Hip width (mm)               | 369±39.563        |
| Popliteal height (mm)        | 474±34.926        |
| Buttock popliteal depth (mm) | 499±37.329        |

### Materials

Figure 4.1.1(a) depicts the experimental setup within a grounded Boeing 737 cabin. A maximum of four participants joined the experiments simultaneously, seated in 9B, 9C, 9D, and 9E. A loudspeaker (Type: Mackie Thump 15BST) was positioned behind Row 9. The distance between the speaker and Row 9, as well as the volume of the speaker, were controlled to replicate the conditions recorded in a real ATR 72-500 flight (Müller et al., 2022): 82.6 dB(A) at the Row 9 aisle seats (Seats 9C and 9D), and 84.6 dB(A) for the window seats (Seats 9B and 9E). Figure 4.1.1(b) shows a photo of the experiment setup.

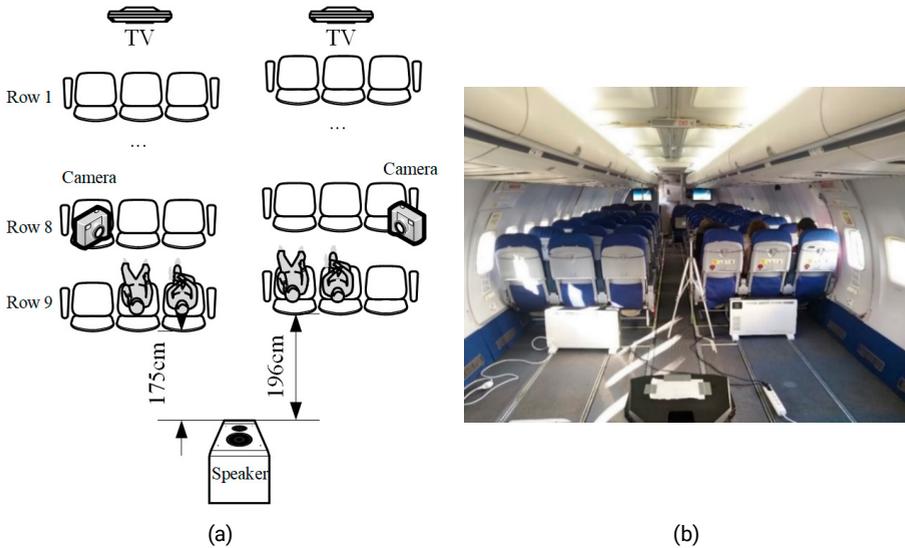


Figure 4.1.1: Experiment setup

Table 4.1.2: Average SPL of each seat. Unit is in dB(A), measured by B&K® 2270 Sound Level Meter

| Seat Number   | 9B   | 9C   | 9D   | 9E   |
|---|------|------|------|------|
| Jet engine recording (Boeing 737 sound, with turboprop SPL)(C1) | 84.6 | 86.1 | 86.0 | 84.2 |
| Recording Turboprop (ATR 72-500)(C2, 3 and 4)                   | 86.3 | 84.9 | 84.8 | 86.3 |

Four distinct conditions were established, with the average SPL distribution (measured in dB(A)) across the seats presented in Table 4.1.2. Condition 1 (C1) served as the control scenario, featuring a jet sound recording (Boeing 737) played at the same SPL as the turboprop. In Condition 2 (C2), a turboprop sound recording (ATR 72-500) was used. Conditions 3 (C3) and 4 (C4) introduced turboprop sounds, along with ANC headphones and earplugs, respectively. In Condition 3 and 4, a Bose® NC 700 (Fig. 4.1.2a) and Mack’s® Slim Fit Soft Foam earplugs (Fig. 4.1.2b) were used, respectively. The choice for the Bose® NC 700 headphones was based on an evaluation that it was selected as the most comfortable headphones on the market at that time (Dragan, 2022). The Mack’s® Slim Fit Soft Foam earplugs were selected since this earplug is the most comfortable and best for filtering out airplane noise according to the New York Times (Morrison, 2020). The seats used were the current KLM Boeing 737s Recaro seats.



**Figure 4.1.2:** Bose® noise cancelling 700 headphones (a), and Mack's® Slim Fit Soft Foam earplugs (b)

### Questionnaires

Seven types of questions/questionnaires were employed in the experiment, and they are listed in Table 4.1.3. In addition to these existing questionnaires, a newly developed Ear Local Discomfort (ELD) questionnaire (Q4) was used to assist participants in localizing discomfort around the ear, as shown in Figure 4.1.3. The regions around the ear were defined based on ear anatomy and critical interaction areas for over-ear headphones and in-ear headsets, following the descriptions of Stavrakos et al. (2015). The Likert scale used in the ELD questionnaire was inspired by the Local Postural Discomfort (LPD) questionnaire (Anjani et al., 2021). All questions were asked while the participants were still in the airplane in the seat to prevent that memory will play a role in scoring as Mansfield et al. (2020) showed that memory errors can creep in once a participant leaves their seat.

Table 4.1.3: Questions/questionnaires asked during the test

| Question number | Question  | Rating scale  | Reference   |
|-----------------|---|---|---|
| Q1              | Rank the different conditions according to your preference.   |   | Self-composed   |
| Q2/Q3           | Give your overall comfort/discomfort rating over the last 42min.  | Scale of one to ten. 1=no comfort, 10=extreme comfort   | Adopted from Anjani et al. (2021)   |
| Q4              | Ear Local Discomfort (ELD) using the image in Fig. 3. please identify your discomfort for each body area indicated. | 1=not uncomfortable, 2=slightly uncomfortable, 3=discomfortable, 4=very discomfortable, 5=extremely discomfortable. | Based on the local posture discomfort questionnaire from Anjani et al. (2021) |
| Q5              | Identify anything which is causing you discomfort at this moment.   | Open question   | Adopted from (Vink et al., 2022)  |
| Q6              | Mark the three factors most contributing to your experienced level of discomfort.                                   | Choose from the options: Temperature, Noise, Lighting, Air quality, Vibration, Seat, Space                          | Adopted from (Vink et al., 2022), based on (Bouwens et al., 2018)             |
| Q7              | Why would or wouldn't you want to wear ANC headphones or earplugs again on an airplane?                             | Open question   | Self-composed   |

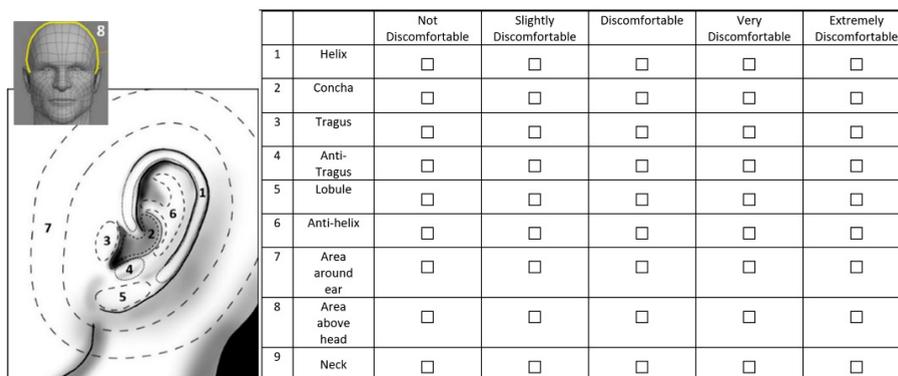


Figure 4.1.3: human ear/head areas as used in Q4 (ELD), based on Stavrakos et al. (2015) and LPD (Anjani et al., 2021)

## Protocols

The research protocol is shown in Fig. 4.1.4. After acquiring informed consent, the basic anthropometrics of each participant were measured according to the procedure described by Molenbroek et al. (2017). Participants underwent four sessions, each taking place in the same seat. Each session consisted of 45 minutes of noise exposure under one of the four conditions using the Latin square to define the order, followed by a 15-minute break. At specific time intervals within each session (T0, T15, T30, and T45), participants were required to complete questionnaires as outlined in Figure 4.1.4. Additionally, they were asked to fill out Q1 and Q6 at the end of all sessions. Besides filling out questionnaires, participants had the option to relax or engage in activities like reading from a tablet, phone, or book. After each condition, participants were instructed to leave the fuselage temporarily, take a short walk, visit the restroom, or have a drink. They were not allowed to remain in their seats during this time. To ensure the correct usage of the earplugs, participants were provided with instructions.

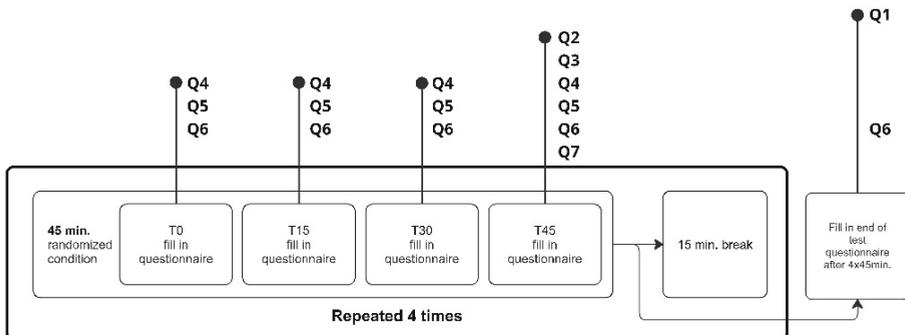


Figure 4: research protocol.

## Data analysis

The data analysis was conducted using SPSS® 28. The normality of the data was assessed using the Shapiro-Wilk test. Differences between normally distributed data were analyzed using the paired t-test, while the Wilcoxon signed-rank test was employed for non-normally distributed data. For questions Q1, Q2, Q3, and the ELD score over time a Bonferroni correction was added. Additionally, correlations for the ELD scores, the comfort/discomfort scores, and participant anthropometrics in C3 and C4 were determined using the Pearson correlation coefficient.

## Results

The outcomes of the Wilcoxon signed rank and paired t-tests for the comfort, discomfort, and preference scores are presented in Table 4.1.4. Table 4.1.4 shows the p-value with and without the Bonferroni correction, for the following data description the p-values without the correction are used. Participants reported statistically significant ( $p < .05$ ) higher comfort, and lower discomfort scores for C3 and C4 compared to C2, as shown in Fig. 4.1.5. This trend is supported by the preference score (Q1) at the end of the test (Fig. 4.1.6).

Table 4.1.4: Q1, Q2 and Q3 pairwise comparison of conditions. P-values for the paired t-test of the comfort score. P-values for the Wilcoxon signed ranks test of the discomfort and the preference score. The values with a Bonferroni correction are added on the right side. Significant values ( $p < .05$ ) are marked with \*.

|   | Comfort (N=24)<br>Sig. (2-tailed) | Discomfort (N=24)<br>Sig. (2-tailed) | Preference (N=22)<br>Sig. (2-tailed) |
|---|-----------------------------------|--------------------------------------|--------------------------------------|
| Turboprop (C2) - Turboprop + ANC (C3)           | <.001*/<.001*                     | <.001*/.005*                         | <.001*/.004*                         |
| Turboprop (C2) - Turboprop + Earplug (C4)       | .102/.614                         | .032*/.194                           | .025*/.151                           |
| Turboprop (C2) - Jet Engine (C1)                | .472/1.000                        | .165/.991                            | .009*/.051*                          |
| Turboprop + ANC (C3) - Turboprop + Earplug (C4) | .017*/.104                        | .127/.764                            | .058/.349                            |
| Turboprop + ANC (C3) - Jet Engine (C1)          | .001*/.008*                       | .017*/.105                           | .059/.352                            |
| Turboprop + Earplug (C4) - Jet Engine (C1)      | .484/1.000                        | .505/1.000                           | .908/1.000                           |

\*Significant:  $p < .05$

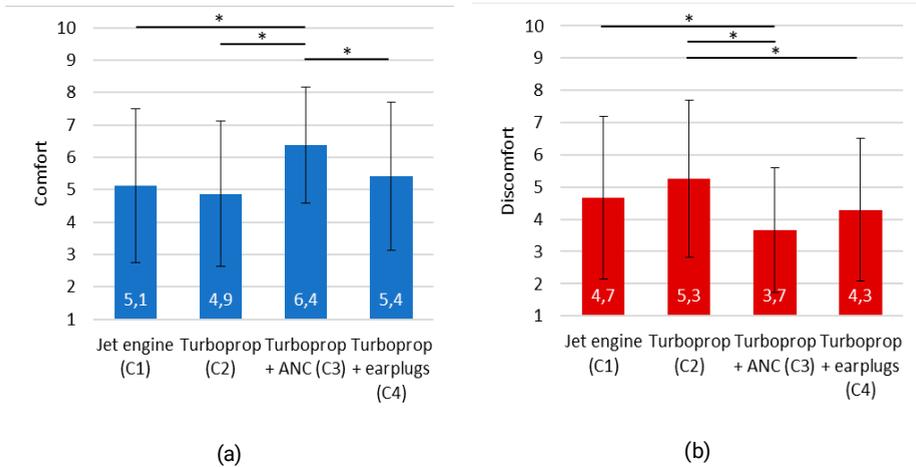


Figure 4.1.5: Comfort (a) and discomfort (b) rating per condition after 45min., 1=no comfort, 7=extreme comfort, 1=no discomfort, 7=extreme discomfort. Significant ( $p < .05$ ) results are marked with \*.

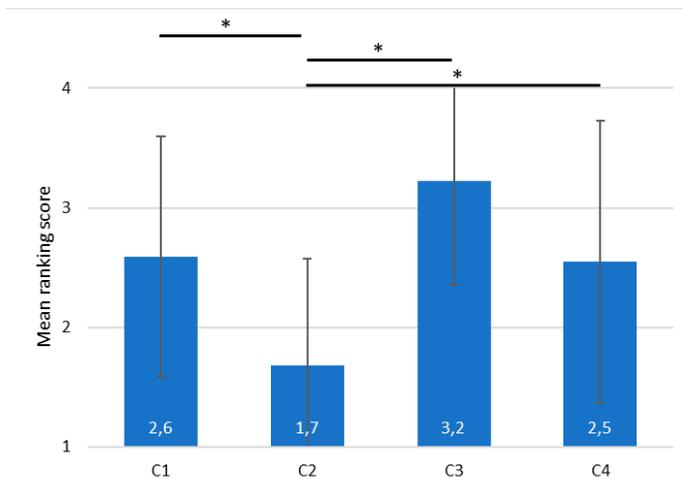


Figure 4.1.6: The condition preference at the end of the test (Q1). The ranked conditions were given a score where ranking 1 would get 4 points, 2=3, 3=2 and 4=1. Significant ( $p < .05$ ) results are marked with \*.

Furthermore, the condition involving ANC headphones (C3) demonstrated higher comfort and lower discomfort than the jet engine sound (C1), with a significant difference ( $p < .05$ ). However, when it comes to preference, the difference is not statistically significant. In terms of comfort, ANC headphones outperform earplugs ( $p < .05$ ). For discomfort and preference, similar trends were observed, although the differences are not statistically significant.

The ELD scores reveal that while the overall discomfort scores are relatively low (just above and under 2 on a 5-point scale), there are significant differences in various regions between using headphones and earplugs, as shown in Figure 4.1.7. When using earplugs, participants reported significantly higher scores ( $p < .05$ ) in the inner ear regions such as Concha, Tragus, Anti-Tragus, and Anti-Helix than when using ANC headphones. On the other hand, using ANC headphones resulted in significantly higher discomfort scores ( $p < .05$ ) in the areas around the ear, e.g. Helix, Lobule, Around the ear, Above the head, and Neck (Fig. 4.1.7). Over time, there are significant increases (based on uncorrected results) of discomfort for the helix, the anti-helix, around the ear, above the head, and neck area while wearing ANC headphones and for the concha, tragus, anti-tragus, and around the ear while wearing earplugs, as shown in Table. 4.1.5. A comparison of the different discomfort scores over time is also visualized in Fig. 4.1.8.

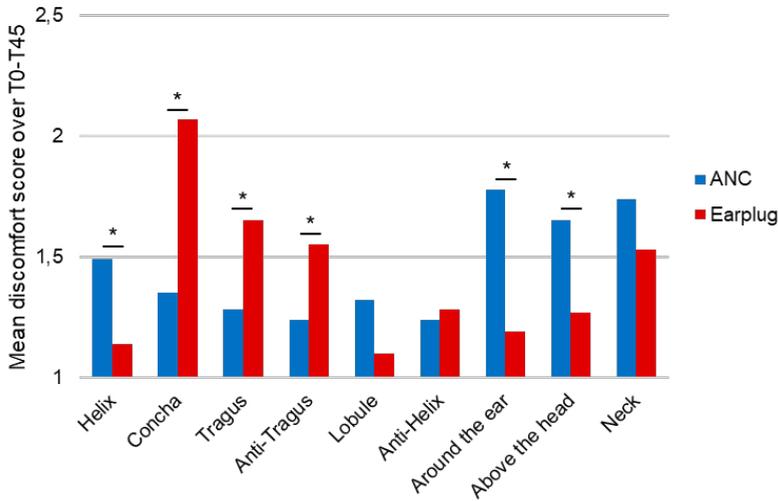


Figure 4.1.7: Ear Local Discomfort (Q4) mean over time, significant ( $p < .05$ ) results are marked with \*.

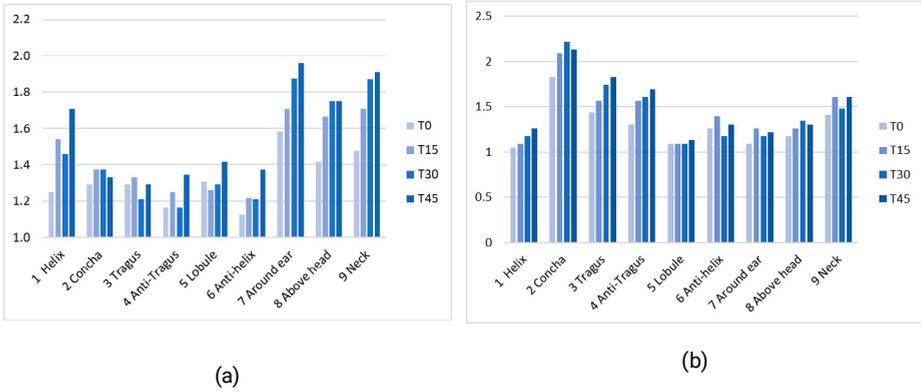


Figure 4.1.8: Ear Local Discomfort (Q4) over time of C3 ANC headphones (a) and C4 Earplugs (b)

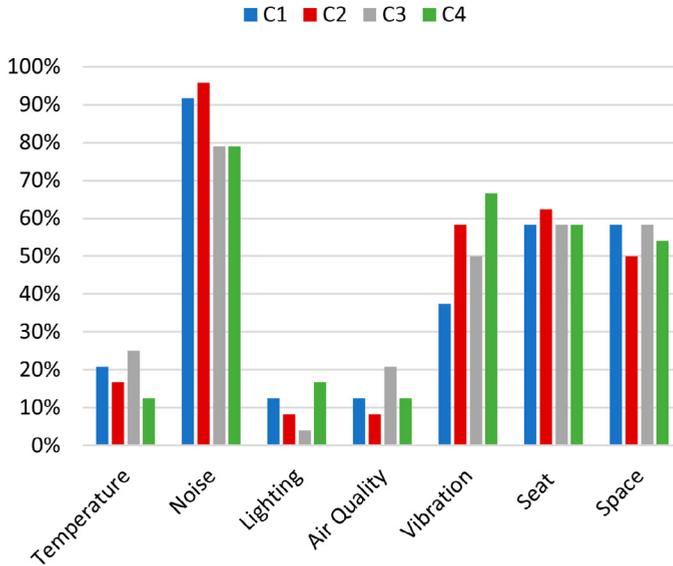


Figure 4.1.9: Percentage of 24 participants choosing the factors contributing to the experienced level of discomfort at T45 (Q6).

Table 4.1.5: Uncorrected p-values Wilcoxon signed rank test, testing changes over time in ELD scores. Significant values ( $p < .05$ ) are marked with \*.

| (Sig.2 tailed) | ANC   |       |        |        |        |        | Earplugs |       |       |        |        |        |
|----------------|-------|-------|--------|--------|--------|--------|----------|-------|-------|--------|--------|--------|
|                | T0-15 | T0-30 | T0-45  | T15-30 | T15-45 | T30-45 | T0-15    | T0-30 | T0-45 | T15-30 | T15-45 | T30-45 |
| Helix          | .084  | .190  | .026*  | .317   | .157   | .034   | .317     | .180  | .102  | .317   | .102   | .157   |
| Concha         | .414  | .480  | .739   | 1.000  | .655   | .705   | .034*    | .029* | .124  | .180   | .763   | .480   |
| Tragus         | .705  | .317  | 1.000  | .257   | .705   | .157   | .257     | .052  | .029* | .046*  | .034*  | .317   |
| Anti-Tragus    | .414  | 1.000 | .157   | .414   | .083   | .102   | .058     | .035* | .021* | .655   | .257   | .157   |
| Lobule         | .317  | .705  | .763   | .564   | .257   | .083   | 1.000    | 1.000 | .564  | 1.000  | .564   | .317   |
| Anti-Helix     | .414  | .414  | .096   | 1.000  | .083   | .046*  | .414     | .317  | .739  | .157   | .726   | .180   |
| Around the ear | .257  | .071  | .038*  | .102   | .083   | .480   | .046*    | .317  | .257  | .157   | .564   | .317   |
| Above the head | .034* | .011* | .033   | .317   | .317   | 1.000  | .157     | .157  | .083  | .414   | .317   | .785   |
| Neck           | .014* | .014* | .004** | .317   | .102   | .655   | .206     | .739  | .160  | .083   | 1.000  | .334   |

\*Significant:  $p < .05$

\*\*Significant after Bonferroni correction

Tables 4.1.6 and 4.1.7 display the Pearson correlation coefficients among the ELD scores, the comfort/discomfort scores, and participant anthropometrics in C3 and C4, respectively. In the scenarios using ANC (C3), we observed weak ( $>0.3$ ) to moderate correlations ( $>0.5$ ) between the ELD scores and the overall discomfort scores, along with inversely weak correlations ( $<-0.3$ ) to moderate correlations ( $<-0.5$ ) between the ELD scores and the overall comfort scores. However, in the case of earplugs (C4), such relationships were not observed.

Table 6: Pearson correlation coefficient of turboprop with ANC Headphones Q2, Q3, and Q4.

| ANC Headphones     | Helix  | Concha | Tragus | Anti-Tragus | Lobule | Anti-Helix | Around the ear | Above the head | neck   | Overall Comfort | Overall Discomfort |
|--------------------|--------|--------|--------|-------------|--------|------------|----------------|----------------|--------|-----------------|--------------------|
| Concha             | 0.724  |        |        |             |        |            |                |                |        |                 |                    |
| Tragus             | 0.677  | 0.569  |        |             |        |            |                |                |        |                 |                    |
| Anti-Tragus        | 0.44   | 0.57   | 0.724  |             |        |            |                |                |        |                 |                    |
| Lobule             | 0.511  | 0.419  | 0.648  | 0.478       |        |            |                |                |        |                 |                    |
| Anti-Helix         | 0.5    | 0.606  | 0.823  | 0.807       | 0.505  |            |                |                |        |                 |                    |
| Around the ear     | 0.657  | 0.617  | 0.536  | 0.31        | 0.487  | 0.403      |                |                |        |                 |                    |
| Above the head     | 0.583  | 0.461  | 0.717  | 0.476       | 0.487  | 0.614      | 0.704          |                |        |                 |                    |
| Neck               | 0.682  | 0.761  | 0.599  | 0.693       | 0.238  | 0.601      | 0.639          | 0.667          |        |                 |                    |
| Overall Comfort    | -0.21  | -0.371 | -0.327 | -0.438      | -0.204 | -0.502     | -0.411         | -0.485         | -0.548 |                 |                    |
| Overall Discomfort | 0.237  | 0.386  | 0.372  | 0.454       | 0.216  | 0.537      | 0.39           | 0.434          | 0.536  | -0.934          |                    |
| Stature            | -0.196 | -0.236 | -0.01  | -0.029      | 0.033  | -0.002     | -0.156         | -0.1           | -0.168 | 0.1             | -0.089             |
| Age                | -0.246 | -0.119 | -0.105 | 0.045       | -0.247 | 0.084      | -0.156         | 0.048          | 0.012  | -0.24           | 0.082              |

Table 7: Pearson correlation coefficient of turboprop with Earplugs Headphones Q2, Q3, and Q4.

|                    | Helix  | Concha | Tragus | Anti-Tragus | Lobule | Anti-Helix | Around the ear | Above the head | neck   | Overall Comfort | Overall Discomfort |
|--------------------|--------|--------|--------|-------------|--------|------------|----------------|----------------|--------|-----------------|--------------------|
| Concha             | 0.588  |        |        |             |        |            |                |                |        |                 |                    |
| Tragus             | 0.449  | 0.669  |        |             |        |            |                |                |        |                 |                    |
| Anti-Tragus        | 0.558  | 0.67   | 0.911  |             |        |            |                |                |        |                 |                    |
| Lobule             | 0.937  | 0.556  | 0.397  | 0.591       |        |            |                |                |        |                 |                    |
| Anti-Helix         | 0.513  | 0.503  | 0.71   | 0.816       | 0.62   |            |                |                |        |                 |                    |
| Around the ear     | 0.692  | 0.594  | 0.217  | 0.408       | 0.769  | 0.359      |                |                |        |                 |                    |
| Above the head     | 0.704  | 0.533  | 0.618  | 0.776       | 0.775  | 0.831      | 0.647          |                |        |                 |                    |
| Neck               | 0.424  | 0.579  | 0.425  | 0.519       | 0.583  | 0.644      | 0.758          | 0.66           |        |                 |                    |
| Overall Comfort    | -0.077 | -0.007 | -0.098 | -0.175      | -0.144 | -0.093     | -0.057         | -0.284         | -0.027 |                 |                    |
| Overall Discomfort | -0.023 | -0.059 | 0.077  | 0.16        | 0.054  | 0.095      | -0.075         | 0.229          | -0.037 | -0.867          |                    |
| Stature            | -0.225 | -0.464 | -0.069 | -0.091      | -0.205 | -0.151     | -0.394         | -0.327         | -0.292 | 0.231           | -0.141             |
| Age                | -0.066 | -0.297 | -0.168 | -0.201      | 0.007  | 0.016      | -0.042         | 0.055          | 0.041  | -0.101          | 0.029              |

Table 4.1.8 gives a qualitative overview of Q5 and Q7. Most participants mentioned that the disadvantages of using ANC headphones are pressure on the head, weight, neck pain, vibration, sweating, and a feeling of low air pressure. For earplugs, besides blocking social communications (reduced speech recognition), participants reported itchiness and an unfamiliar feeling around the Concha region.

Table 4.1.8: Advantages and disadvantages deducted from Q5 and Q7

|               | ANC headphones  | Earplugs  |
|---------------|---|---|
| Advantages    | <ul style="list-style-type: none"> <li>- Enables listening to entertainment</li> <li>- Effective noise cancellation</li> <li>- Clean</li> <li>- Easy to remove</li> <li>- Helps to focus on a task (e.g. reading)</li> </ul>  | <ul style="list-style-type: none"> <li>- Lightweight</li> <li>- Easy to wear</li> <li>- Does not add pressure on the head</li> </ul>    |
| Disadvantages | <ul style="list-style-type: none"> <li>- Puts pressure on the head and around the ears</li> <li>- Weight of the headphones</li> <li>- Neck pain due to the weight</li> <li>- Vibration is noticed more and can lead to an uncomfortable feeling to the heart.</li> <li>- Bad speech recognition</li> <li>- Sweating on the anti-helix</li> <li>- Feeling of low air pressure around the ears</li> <li>- Breaking of the 'sound' seal after jaw movements</li> </ul> | <ul style="list-style-type: none"> <li>- Itchy</li> <li>- Bad speech recognition</li> <li>- Unfamiliar feeling in the Concha</li> </ul> |

In Fig. 4.1.9, the opinions of the participants regarding the factors that contribute to discomfort at T45 are shown (Q6). While wearing ANC headphones and earplugs, the impact of noise on the overall discomfort is reduced, but it remains the most important factor that influences discomfort. We did not find differences between using ANC headphones and earplugs.

## Discussion

The use of either ANC headphones or earplugs has a positive effect on passenger comfort and discomfort by enhancing comfort and reducing discomfort. While there is a preference for ANC headphones over earplugs, it is important to note that this difference is not statistically significant. The ELD scores help define specific discomfort areas for both earplugs and ANC headphones. The discomfort experienced in localized ear areas and general comments suggest that there are additional factors at play, e.g. weight, that do not allow dismissal of the efficacy of earplugs.

### Acoustic comfort in four conditions

Increased comfort, decreased discomfort, and increased preference scores for the conditions with ANC headphones (C3) and Earplugs (C4) are an indication that they help make turboprop airplanes (and possibly future electrical propelled airplanes) a more competitive option compared to jet engine airplanes and improve the overall comfort/discomfort experience. The non-significant preference comparison between ANC headphones and jet-engine airplanes further affirms the effectiveness of using such devices as most participants had previous experience with jet-engine airplanes. The fact that passengers are able to choose a sound reduction system such as headphones and earplugs in itself might have a positive effect on comfort and discomfort as Bouwens et al. (2021) state that being in control of noise levels can improve airplane comfort.

Between earplugs and ANC headphones, there is a general preference for the ANC headphones. But it cannot be concluded if this is because of the comfort of the wearable or because of the better blocking of the sound. In Q6 it is seen that the impact of noise on discomfort is the same for both conditions, but in the open questions 'the effectiveness of noise cancellation' was mentioned as

an advantage of ANC. For comfort, ANC headphones score significantly better than earplugs, but for discomfort and preference, this is not true. It could be that wearing headphones has a larger impact on discomfort than on comfort, which can be explained by discomfort being more associated with pain or numbness, and comfort is more associated with relaxation and emotional well-being (Zhang et al., 1996). Although some device-specific discomfort aspects could be clearly defined, future research might include a condition without noise. This way the impact of wearable-specific discomfort factors and the environment factor 'noise' on overall comfort and discomfort could be split up and clarified. Additionally, the effect of time on the willingness to use these devices could be further explored. Within the duration of wearing the devices (45 minutes.), in some areas a significant increase over time was observed. In a longer flight scenario, this effect might lead to higher discomfort levels.

### **Factors that influence the choice between ANC headphones and earplugs**

The ELD question together with the text analysis supported identifying specific discomfort areas. They also gave insights about participants' preference towards ANC headphones or earplugs. The headphones create more discomfort around the ear and above the head while the earplugs create more discomfort inside the ear. This was further confirmed by the open questions (e.g. neck pain, pressure on the head and around the ears, or an unfamiliar feeling in the Concha). The preference is personal and individuals can have strong reasons not to wear headphones or earplugs (e.g. feeling of low air pressure with ANC headphones or itchy earplugs). Thus providing a choice to passengers is preferred. These findings correspond with the proposed guidelines from Hsu et al. (2004) to improve the design of hearing protection. Hsu et al. (2004) proposes the following attention points to improve comfort: Airtightness, weight, heat sinking ability, texture, headband force, and improving possibilities to converse.

Another factor mentioned as a disadvantage of the ANC headphones was 'a feeling of low air pressure'. Butterworth & Dragan (2019) describe this phenomenon as "eardrum suck". In their test, 52% experienced this effect. This effect is psychosomatic, there is no measurable air pressure difference. This is something to consider as well when providing ANC headphones to passengers.

### **Research methods**

Vink et al. (2022) reported that the factors influencing discomfort in a turboprop airplane (in order of importance) are: noise, vibration, seat, temperature, space, air quality, and lighting. In our research for the condition with only turboprop noise, this order is: Noise, seat, vibration, space, temperature, air quality, and lighting. Although there are slight differences, the top 3 is highly comparable. As the main objective of this research is 'acoustic comfort' this outcome shows

that the research setup for this purpose is sufficient. The research of Vink et al. (2022) took place in an actual airplane with more airplane-specific vibrations, which could explain the differences in the vibration outcome.

During the analysis, we present both the outcomes with and without a Bonferroni correction. However, in the subsequent discussion and conclusion, we primarily focus on the uncorrected results. While there exists a heightened risk of type one errors, given the research area's alignment with existing literature in the area of comfort research (Fiorillo et al., 2021)(Varela et al., 2019), it might not be absolutely imperative to avoid type one errors (Armstrong, 2014). On the other side, with a potentially increased likelihood of type two errors, there might be a chance of overlooking the opportunities introduced by using earplugs.

The dB(A) was slightly different across the seats. Although in a real flight there are also differences in dB(A) between seat locations (Müller et al., 2022), this fact made it impossible to make a between subject comparison. Therefore, a future study should consider either further equalize SPL levels across seats or search for a relation between seat location and acoustic comfort experience.

In evaluating the performance of the hearing protection a subjective approach was taken, by using a questionnaire. Although appropriate in this context, as the perception of passengers will eventually define their satisfaction, scientifically it could be relevant to add an objective dimension. Valentin et al. (Valentin et al., 2024) underscored the importance of objective measurements when evaluating the impact of sound environments on performance and effectiveness of hearing protection. Thus it is relevant to quantify the performance of these specific devices in absolute values in this specific use case. A microphone in a real ear technique (MIRE), or a manikin as described by respectively ISO 11904-1 and ISO 11094-2 (ISO, 2002, 2004) could be used to measure the sound level on the inside of the hearing protection close to the ear.

The body map of the ear seems quite useful in this study. Further research might be needed to study the usefulness of the ear sensitivity. Also, Smulders et al. (2023) states that future work might want to investigate on and around the ears for headphone design.

### **Design implications**

The use of ANC headphones in daily life has gained significant popularity. However, it is important to recognize that not everyone has access to ANC headphones. Airlines can play a crucial role in enhancing the comfort of passengers and increasing their willingness to fly on turboprop aircraft by providing ANC headphones. It is worth noting that the effectiveness of ANC

headphones in specific situations can vary based on the brand and model of the headphones. In fact, using an inappropriate model may even lead to an increase in sound levels (dB(A)) (Ang et al., 2017). Therefore, it is advisable for airlines to provide specific tested models of ANC headphones and the associated instructions to passengers to ensure optimal noise cancellation and improve the comfort of passengers.

As a relatively low-cost solution, it might be beneficial for airlines to offer earplugs since a positive effect is also shown for earplugs. However, the best type of earplug and how it should be introduced needs to be studied further as Casali (2012) states that proper fit to the user's ears and training in insertion procedures are critical to the success of earplugs.

When larger adjustments in the airplane cabin are possible, it could be considered to look into placing noise cancellation into the head rest or seat (Dimino et al., 2022) or integrating noise cancelling panels into the airplane interior (Arena et al., 2017), and in this way reduce noise and device specific discomfort.

### **Limitations**

The choice to compare ANC headphones and earplugs was made to provide a contrast between an ANC device and a readily implementable noise reduction option. In future research, it may be beneficial to explore a wider range of options, including ANC earbuds and passive noise-canceling headphones.

During the research, the participants did not get a specific task. They were only asked not to do any tasks involving sound, because of the nature of the research. It should be considered that the specific activity of participants can impact the outcomes, for instance, Smulders & Vink (2021) describe that under higher workload, participants reported higher acoustic discomfort. Certain activities such as viewing a VR environment, can also serve as a distraction to other discomfort factors, although more effective for distracting from a restricted space than noise disturbances (Lewis et al., 2016). In this study the advantage of using ANC headphones in concentrating tasks was mentioned by participants. Concurrently this study did not consider social factors during the test. Participants were allowed to engage in conversations with each other, but the impact of these interactions on device preference was not recorded, although in the open questions difficulty in communication was mentioned for both ANC headphones and earplugs as a disadvantage. On the work floor having communication difficulties is considered uncomfortable (Hsu et al., 2004), but according to others background conversations are found annoying (Bouwens et al., 2021). Moreover, ANC devices offer extra options for entertainment, which could be a valuable area of investigation in future research.

Additionally, the earplug choice could be studied further as there are many earplugs available, and differences between them regarding fit, the way of placing them (Casali, 2012) and application in an aircraft might lead to a specific preferred type and instruction, which was not studied in our research. Besides an instruction for using the earplugs, the placement was not checked by the researchers. Incorrect placement could provide negligible attenuation (Casali, 2012), which could have a negative impact on the comfort and discomfort experience, but since the participants did receive instructions for checking a correct fit themselves, this might be a minor risk.

It is also important to note that this test did not take place in a flying airplane, and as such, sound perception may differ from a real-life setting. In a real flight vibrations and sound both could amplify each other (Aggarwal et al., 2022). In this research the participants only experienced sound, and there was for instance an absence of engine vibrations, which could have influenced the outcomes. The test setup involved a directional sound source directed at the back of the participants, and some reported variations in sound perception between their ears. In an actual flight, the sound environment might be more omnidirectional. Additionally, the average age of the participants in this study was approximately 27, and it is known that the sensitivity of human hearing decreases with age (International Standards Organisation (ISO), 2017). Considering this, the effects of earplugs and ANC headphones might vary for individuals in different age groups than those studied in this experiment.

## Conclusion

Active noise cancellation headphones and earplugs can improve the comfort experience of passengers in turboprop aircraft. The use of these wearables increases overall comfort, reduces discomfort, and is preferred over not wearing any hearing protection on turboprop flights. Between them, ANC headphones are slightly preferred over earplugs. ANC headphones have a better performance regarding filtering noise, but both options bring their own specific limitations. Participants wearing the ANC headphones experienced more discomfort around the ears and on the head compared to using the earplugs where they experienced more discomfort in the area inside the ear. The preference is personal, and individuals can have strong reasons not to wear headphones or earplugs (eardrum suck in case of ANC headphones, or itchiness in case of earplugs), thus providing a choice to passengers is preferred.

Scientifically, this study shows that it is useful to add a body map of the area in and around the ear to study the effects on (dis)comfort in that area.

## Ethical Considerations

The experiment protocols were approved by the human research ethical committee of Delft University of Technology under ID number 1953. As the experiment took place around February 2022, the following measurements were taken to minimize the risk of COVID-19 infection: 1) people with an age  $\geq 65$  were excluded due to the higher risk of complications from COVID-19; 2) all participants were fully vaccinated and filled a health declaration form to indicate that they did not have COVID-19 symptoms and 3) they wore a facemask during the test.

## Informed consent

All participants involved in this study signed an informed consent form before participating in this study.

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## Conflict of Interest

The authors declare that they have no conflict of interest.

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## **4.2. Towards a more efficient train use: A VR case study evaluating a comfortable night/day train design.**

### **Abstract**

Twenty four young participants (average age 26.5 years) evaluated 12 train interiors for night and 4 for day trains in a VR environment. The interiors had for instance different shielding between the seats and beds. Participants had to select the preferred layout and explain why. The results show a difficult balance between privacy and security within the day and night train interior. Privacy is important, especially in the night train. Although women tend to prioritize safety. A low or a high 'back wall' in between seat rows is mostly preferred over no wall during the night. Next to that, a high back wall is mostly preferred over a closed compartment and some people prefer only shielding at their head area instead of the full length of the bed. Another aspect that is more important for the night train is noise cancellation. Next to privacy, the possibility of having interaction with other train passengers and a spacious look is relatively more important in a day train. This study gives a first impression of factors that are of influence to the privacy and security experience in day and night train travel. For future studies, it is advised to use a real train environment with participants of various ages, as this study was done in VR with young participants, and choose a limited interior change to enable a more systematic review of the results.

## Introduction

The path towards a sustainable society is still uncertain. One thing is certain: mobility must become sustainable. The night train is a more sustainable alternative to flying and a suitable replacement for trips up to 2000km (Goeverden et al., 2019), and 38% of all flights departing from the largest airport in the Netherlands are within a range of 750km (Donners & Kantelaar, 2019). However, operating a night train profitably is not an easy task (Roel, 2023). Night train carriages cannot be used during the day, or in day trains it is hard to sleep during the night. Besides travel time and travel cost, the comfort level of the interior is important in choosing between an airplane or a night train (Vink et al., 2022). According to Kantelaar et al. (2022), perceived night train comfort is most influenced by the accommodation of privacy, and privacy and security are important for comfort in sleeper trains (Out & Hiemstra-van Mastrigt, 2024). Moreover, additional issues like comfort with sleeping, personal security, and sharing cabins matter (Buh and Peer, 2024). It is unknown which elements in the train interior contribute to privacy and security. Therefore, this research looks into the privacy and security needs during day and night train travel by changing interior elements in a VR train environment.

## Method

To arrive at a more sustainable travel, a case study was performed in designing a convertible train interior (convertible between day and night), and the opinion of end-users on the interior was gathered. Different train coach interior layouts were designed for day and night with various shielding elements. The sense of privacy and security was evaluated. Twenty-four participants (average age  $26.5 \pm 14.4$ ; 10 male, 14 female, 10 had experience in the night train) experienced the different layouts of the train coach in VR. A three-dimensional train coach was modelled in Blender, incorporating 16 different layouts, including 4 daytime scenarios and 12 nighttime scenarios (see Figure 4.2.1 for three examples of the nighttime scenario). The layouts mainly differed in the type of shielding between seats. Remembering 16 different layouts is impossible for end-users. Therefore, during the VR experience, the scenarios were presented to the participants in pairs, from which they had to choose the one scenario they preferred until they had seen all scenarios, and the best one remained. For the remaining scenario, the participants had to rate orally the privacy and feeling of security in the scenario that was chosen in the end: *'Rate the design on your feeling of privacy from 1-10 and explain why? (1 is no privacy and 10 is full privacy).'* And *'Rate the design on your feeling of security from 1-10 and explain why? (1 is no security and 10 is full security).'*

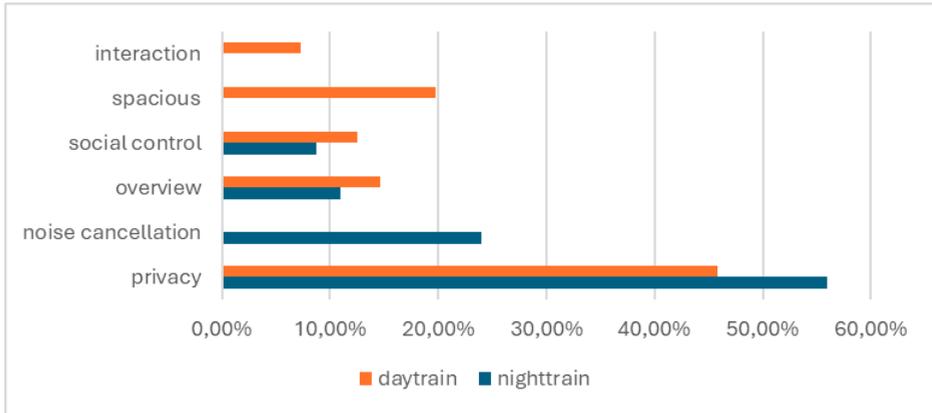
This routine was repeated for 4 day scenarios and 12 night scenarios separately. Additionally, the luggage storage preferences for nighttime travel and daytime travel were asked. The open questions were analysed by clustering and counting the positive and negative reasons. The descriptive statistics were calculated using Microsoft Excel.



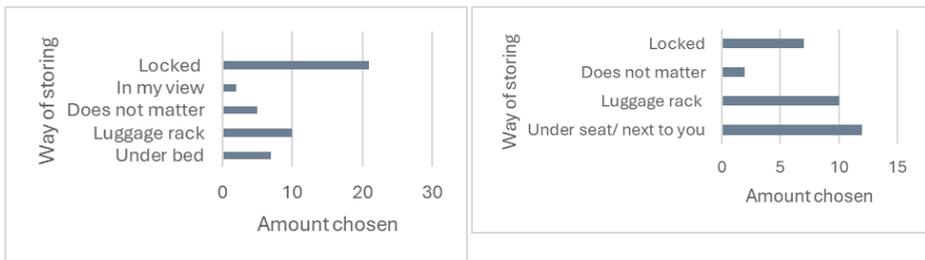
Figure 4.2.1. Three of the 12 nighttime scenarios as shown to the participants in VR. Left: only a high back wall, middle: a quite high back wall and a shielding at head level between two beds, and right: a high back wall and a low shielding between two beds.

## Results

The main reason for choosing a scenario by the 24 participants appeared to be privacy (see Fig. 4.2.2). In the interviews this 'privacy' aspect was explained. A low or a high 'back wall' is mostly preferred over no wall during the night. Next to that, a high back wall in between seat rows is mostly preferred over a completely closed compartment, and some people prefer only shielding at their head area instead of the full length of the bed. There was a difference between male and female, with men generally preferring enclosed spaces at night while women tend to favour more open environments at night. Another aspect that is more important for the night train is noise cancellation. The possibility of having interaction with other train passengers and a spacious look is more important in a day train. Although safety was not explicitly mentioned, 'social control' and 'overview' are considered to be related to the feeling of safety; if counted together, this becomes the second most important factor. Additionally, some participants mentioned that oppressive feelings should be avoided by day, and being too close to other participants during day and night. When the interior included shielding completely around the sleeping area, some participants even described the area as 'feeling like a coffin'.



**Figure 4.2.2.** Percentage of the total number of times a reason is mentioned for choosing a scenario in a day- and night train by the 24 participants (each participant evaluated the night train as well as the day train).



**Figure 4.2.3.** The number of times a way of luggage storage was chosen for nighttime travel (left) and for daytime travel (right)

The preferred place for luggage storage differed for the night and day train (see Fig. 4.2.3). At night, more passengers want their luggage locked, while during the day, people prefer to have the luggage under the seat as it is easily reachable.

## Discussion

The results of this study emphasize the importance of privacy and security within train interiors. And shows a delicate balance between privacy and security. This corresponds with the literature where it is described that the feeling of privacy and security in night trains is found to have a major impact on the sense of comfort (Kantelaar et al., 2022). For most people, having their luggage locked at night is important, for daytime, a lock is not always necessary.

This study shows that shielding around the seat is preferred for privacy reasons. Other studies also show the importance of shielding in transport. Medeiros et

al. (2022) showed, for instance, that passengers even try to shield themselves from others with their laptops. The openness is preferred because of the sense of security it gives in the form of social control and creating an overview. This points to the balance between privacy and security. Males vote more for an enclosed environment, while women seem to prefer a (semi) open environment because of more social control during the night. Another study from Condon et al. (2007) also shows the differences in how women and men experience public spaces due to societal attitudes, behaviours and structures that contribute to their feelings of vulnerability.

Comparing the needs between daytime and nighttime travel, the importance of privacy and security differs in this context. For both daytime and nighttime travel, having a certain amount of privacy and security is important, but passengers' privacy and security needs are higher, and also different, during the night (Flohr et al., 2024). During daytime travel, privacy is most important, but spaciousness and overview is also valued. This can be facilitated by having a partly open environment, e.g. by having a high back wall in between seat rows. During the night, people are not awake, so they prefer to rely on social control and therefore preferably on an open environment, compared to, i.e., sharing a closed compartment with a stranger. Although men in this case find privacy and noise cancellation slightly more important than women do.

Finally, luggage storage was mentioned by the participants. Storage of luggage with a locking mechanism is essential at night, emphasizing the significance of security during nighttime travel. For daytime travel, a lock on luggage is not essential but in some daytime scenarios it can provide extra comfort (for example, on long journeys travelling alone). Next to that, the majority of respondents prefer the top rack as a storage place for luggage for nighttime travel. This preference may be related to easy access to luggage, as well as a sense of space and openness in the traveller's immediate vicinity. For daytime travel, travellers prefer to keep their luggage as close to them as possible (for example, on the seat next to them, under their seat or also in the luggage rack. This is affirmed in other studies as well (e.g. Alberda et al., 2015).

This study has limitations. Not all participants scored all scenarios. Two scenarios were presented to the participants, from which they had to choose the better one until they had seen all scenarios, and one best scenario remained. This means that each participant followed a different protocol. This was done since after showing many scenarios most people do not remember all scenarios and often the last one gets more attention (Do et al., 2008); we can remember only 7-9 scenarios (Miller, 1956). The downside of this approach is the difficulty in comparing between participants. On the other hand, the preferences for

scenarios were rather clear. As a result, no statistical analysis could be made. It is not possible to say scenario X is perceived as significantly more comfortable than scenario Y. Furthermore, the mean age of the participants is around 26 and the study was done using VR. The question is whether, in a real environment and with other age groups the results would be the same, also taking into account the influence of proxemics to other passengers. Moreover, both inexperienced and experienced night train passengers were asked which may also affect the perception of privacy and safety, and thus the choices between layouts.

This study provides insight into feelings of privacy and security within daytime and nighttime train interiors. Train designers could use these results when creating new layouts for daytime and/ or nighttime trains. An idea might be to implement the findings in a design that can be transferred from day train to night train and repeat this study in real life by various age groups.

Future studies could also elaborate on the importance of speech privacy and noise levels in the train carriage environment between day and night, given that noise levels influence the comfort in train interiors (Vledder et al., 2023), and noise cancellation is also mentioned as an important factor in this study. Balancing interior noise with the openness of an environment, could be partially optimized by using interior surface materials for speech privacy (Jang et al., 2016).

Additionally, future studies could explore the influence of cultural differences on the needs for privacy and security in the sleeping environment during transit. Especially for products related to sleep, the comfort experience can be different between cultures (Vink et al., 2021). Sleep habits are cultural dependent, therefore future studies should take this into account.

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CHAPTER

# 5

# DISCUSSION AND CONCLUSION

## 5.1 Main Findings

Within this dissertation, factors influencing (dis)comfort were formulated that need attention to improve occupant comfort/discomfort in propeller airplanes, and for sleeping in automated vehicles or sleeper trains. Several possible solutions are suggested based on the studies and evaluated. Leading to several key findings:

- The main comfort influencing factors are determined in propeller airplanes and compared with findings from previous studies on comfort factors in jet airplanes (chapter 2.1).
- A strong negative effect of noise on the experienced (dis)comfort in propeller airplanes was identified (chapter 2.1).
- The required flat sleeping surface for one night during travelling is defined (chapter 2.2).
- Sleep environment requirements for travel in cars, airplanes, and trains (e.g., privacy, darkness, noise, movement, etc.) are determined for comfortable sleep (chapter 2.2 and 4.2).
- A correction model was generated to compensate for misreported stature or body mass in case anthropometric measurements are impossible and only self-reported data is available (chapter 3.1).
- The sleeping postures and posture variations in different backrest angles are studied for the first time, which is relevant for different travel scenarios (chapter 3.2).
- The relationship between sleep (dis)comfort and the seat backrest angle for sleeping during transit is defined more precisely than described in the current scientific literature (e.g., an SBA of 130° is a minimal requirement for upright sleeping). (chapter 3.2)
- A statistical shape model of the spinal curve in the backrest angles 115° and 140° was developed (chapter 3.3).
- The potential of adding a second pivot joint next to the backrest recline was revealed (chapter 3.3).
- Active noise cancellation and earplugs are proven solutions to dissipate discomfort caused by noise in propeller airplanes (chapter 4.1).
- An Ear Local Discomfort body map was developed, which can be used in future research of discomfort in the context of the ear and the area around the ear (chapter 4.1).

## 5.2 Overview of Results Related to Research Questions

The main research question of this dissertation was: **How can the passenger (dis)comfort experience be improved in future mobility solutions?** This research

question was divided into two key questions. The first, KQ1 ‘What are the (dis) comfort factors that need to be improved?’ addresses the problem space by identifying ‘comfort factors’ in the categories from the Vink and Hallbeck (2012) comfort model: environment, person, product characteristics, and usage/task (Fig. 1.3). The second, KQ2 ‘What are the solutions that could be explored to improve these (dis)comfort factors in the selected mobility solutions?’ focuses on the solution space and identifies potential ‘comfort solutions’. Because many of the studies in this thesis cover both the problem and solution space, just as they partially cross borders between chapter topics (environment, person, product characteristics, and usage/tasks), articles (subchapters) are divided in answering either KQ1, KQ2, or both (as shown in Fig. 5.1).

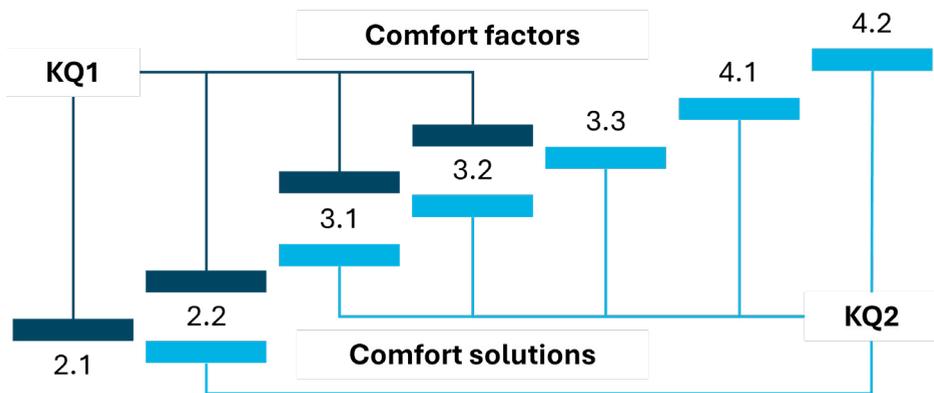


Figure 5.1 Chapters answering KQ1, KQ2, or both.

### 5.2.1 Key question one (KQ1)

The factors influencing comfort and discomfort could have various characteristics. Some are typically physical, like noise and seat hardness, while others are more psychological and emotional like safety and relaxation. Zhang et al. (1996) studied the factors influencing comfort and Looze et al. (2003) discomfort. They state that discomfort is more related to physical factors and comfort more to emotional factors. In this PhD thesis the anthropometrics related to a bed or seat is typically related to the physical aspect, and therefore related to discomfort, while safety and security in e.g., a sleeper train concerns typically a comfort related factor. Within this PhD thesis both comfort and discomfort were studied, through the two key questions. The first key question is: **What are the comfort factors that need to be improved? (KQ1)** This has been explored within the selected different mobility contexts: Turboprop airplanes, night trains, and automated vehicles. For night trains and AVs the research has been focused on the sleeping activity. This is relevant to mention as comfort factors depend on the activity of the passenger (Bouwens et al., 2018). In this sub-chapter elements are taken from the different previous chapters to answer

the first key question. Elements are taken from 'Turboprop acoustic environment (dis)comfort' described in chapter 2, 'sleeping environment' described in chapter 2, 'Personal (anthropometry) characteristics and comfort research' described in chapter 3, and 'Humans in relation to the seat while sleeping in transit' described in chapter 3.

#### *Turboprop acoustic environment (dis)comfort*

In studying factors influencing comfort a hierarchy could be determined. In chapter 2.1, the order of importance of different (dis)comfort factors in propeller aircraft was studied. According to Bubb et al. (2021), discomfort is influenced by six factors: anthropometry, climate, sound, vibrations, lighting, and smell. In chapter 2.1 it was concluded that in a propeller aircraft, the discomfort influencing factors are (in order of importance): noise, the fit between human and seat (anthropometry), vibration, temperature, air quality, and lighting. This shows that the acoustic environment in propeller airplanes is an important factor negatively influencing discomfort. It also shows that the importance of different discomfort and comfort factors is specific to the context, as in jet engine aircraft, the most important comfort factor was found to be 'anthropometrics' (Bouwens et al., 2018). In chapter 2.1, the main comfort influencing factor was 'space'. In the case of the propeller aircraft, the acoustic environment is experienced as very noisy, which overpowers other discomfort factors, as layers in a 'cake' (Mansfield et al., 2020), or as a masking effect (Bubb et al., 2021, p. 145). This means that addressing noise has priority over other discomfort factors. Overall, this confirms the relevance of establishing the environmental factors in the specific situation at hand, as factors influencing comfort and discomfort are environment-specific.

#### *Sleeping environment*

Apart from the environment, the human activity influences the comfort perception. The environmental conditions that are needed for comfort during sleep while travelling are evaluated in chapter 2.2. For sleeping in an airplane, apart from the physical seat factors, the factors noise, temperature, light, smell, and vibration (mentioned in the order of importance) are mentioned (Bouwens et al., 2018) as factors influencing comfort. Vink et al. (2023) found that for a comfortable sleep, 55% mentioned they need darkness, 33% the right temperature, and 28% silence. Caddick et al. (2018) also mentioned that darkness, silence, and a good temperature are important environmental factors needed for sleep. Chapter 2.2 confirms that for sleep, providing a dark environment with the right temperature and relative silence is important. Noise was mentioned as an important factor in airplanes, trains, and cars, although the nature of the sound annoyance might be entirely different. In a propeller airplane, the tonal noise of the engine is the biggest problem (chapter 2.1), in a sleeper

train or jet airplane sound of people talking in the hallway or a door closing in the hallway might be a reason to wake up the passengers (Vledder et al., 2023). This confirms that for each mobility situation, a different strategy is needed to deal with the most important environmental comfort factors. Additionally, in chapter 2.2, movement was mentioned specifically for cars to be disturbing, linked to frequent cornering or shaking of the vehicle, although vehicle vibrations might also have a positive sleep-inducing effect (Bhuiyan et al., 2022). Leading to the overall advice that for sleeping comfort, vehicle speed/movement, noise levels, vibration, and lighting should be balanced and minimized. Also, sudden changes in any factor, such as distinctive sounds and changes in the lighting environment, should be minimized, as sleep can be easily disrupted, and returning to sleep after awakening may be difficult. Ohayon et al. (2010) reported that of the people who experience nocturnal awakenings, 43% have difficulty resuming their sleep afterwards.

#### *Personal (anthropometry) characteristics and comfort research*

It is clear from several studies that the human body size is a factor influencing comfort. For instance, the leg room comfort in an airplane is directly related to upper leg length (Anjani et al., 2020), and at a more generic level, anthropometrics is a factor influencing comfort (Bouwens et al., 2018). The findings in chapter 3.1 are relevant in relation to the anthropometrics. The selection and measurement of anthropometric measurements indirectly have a large influence on the results of comfort research. Chapters 2.1 and 2.2 show that ‘anthropometry’ or ‘the human in relation to the seat’ is an important (dis)comfort factor in all mobility modes. Bubb et al. (2021) related anthropometry to spatial comfort and confinement. Gathering this information is therefore relevant. In chapter 2.1, during the ComfDemo project, 100 participants needed to be selected based on stature and body mass before the test, and anthropometry was measured during the test (in a short timeframe). This study pinpointed a practical problem that is often seen in comfort and ergonomic research. Participants are selected based on self-reported anthropometric data, but during the test, they need to be measured again. Therefore, chapter 3.1 focused on building a model to estimate the actual stature and body mass based on the self-reported data from adults recruited in the Netherlands. Resulting in the conclusion that people slightly overreport their stature and underreport their body mass, especially in the group with a  $BMI \geq 25$ . In ergonomic research, where anthropometric measurements are not possible, and in the recruitment of participants, the suggested models can be used to estimate the actual stature and body mass of the participants based on their self-reported data.

*Humans in relation to the seat while sleeping in transit*

Anthropometrics, as described in the previous paragraph, has a direct relationship to the seat since the size of the seat determines whether a person would fit. However, it is also important to study the comfort specific to the activity or context, for instance, car seat requirements are different for the driving seat compared to the passenger seat (Kilincsoy et al., 2014). When looking more closely at the human in the seat, and the product characteristics within the sleeping task, chapter 2.2 explores the comfort factor 'space', and describes the minimum space that is needed for sleeping in a flatbed situation based on observed sleeping postures (person). The majority of individuals prefer a lateral sleeping position with flexed legs, followed by a supine posture, while prone sleeping is generally the least favoured (chapter 2.2; De Koninck et al., 1983; Skarpsno et al., 2017), and in addition, people vary their position during sleeping (chapter 2.2). This means that for comfort, the size of the bed should facilitate different postures for people with different anthropometric characteristics.

For vehicles where there is less space, looking into sleeping postures in a sitting position is relevant. Therefore, chapter 3.2 evaluated the impact of the backrest recline angle on sleeping postures, sleep movements, and the perceived sleeping comfort. The results in this study indicate that there is a relationship between the seat back recline angle, sleeping posture, and sleeping discomfort, even though the strength varies. This relationship is visualized in **Figure 5.2**. In upright sleeping, most participants sleep with their back straight against the backrest with straight legs, which only changes towards the flat sleeping condition. A more reclined backrest angle increases comfort for sleeping, reduces discomfort (blue line), evokes less distinctive sitting postures (green line), and there is a greater tendency for participants to bend their legs while sleeping and rotate their torsos or lean to the side with their torsos. Additionally, in the most upright angles, participants move more frequently (red line) to dissipate discomfort (blue line), but cannot find a comfortable position so try out more different postures (green line), whereas in reclined angles participants move naturally because increased movement freedom is available (red line), but try out less different postures (green line), since they found a comfortable posture and return to it frequently. This interplay between discomfort, movement, and distinctive postures is facilitated by the centre of gravity of the head and torso, which moves backwards in higher recline angles; by the increase of the torso/leg, and upper leg/lower leg angles, which move more towards a neutral body angle (Han Kim et al., 2019); and by the possibility to rotate the torso to left and right or by laterally bending the torso, making it possible to take lateral postures in a reclined backrest angle (**Fig. 5.2**). Additionally, in 110° and 120° BMI had a negative correlation to crossed legs, and the elbow to elbow width shows a negative correlation to a rotated or asymmetric trunk posture in 110° to 150°.

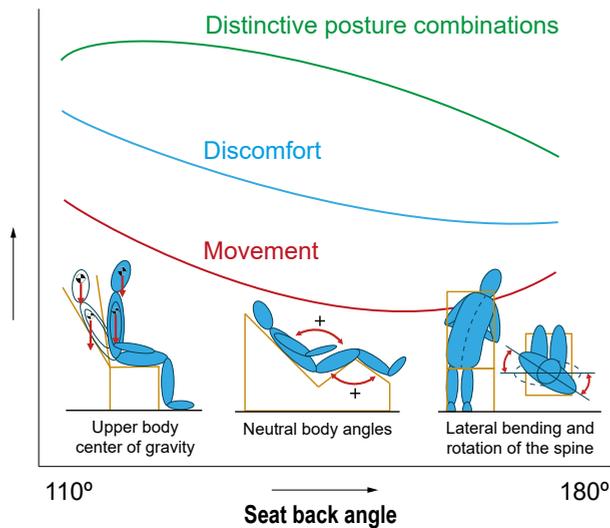


Figure 5.2 Interplay between movement (position shifts), discomfort, and distinctive posture combinations

### 5.2.2. Key question two (Q2)

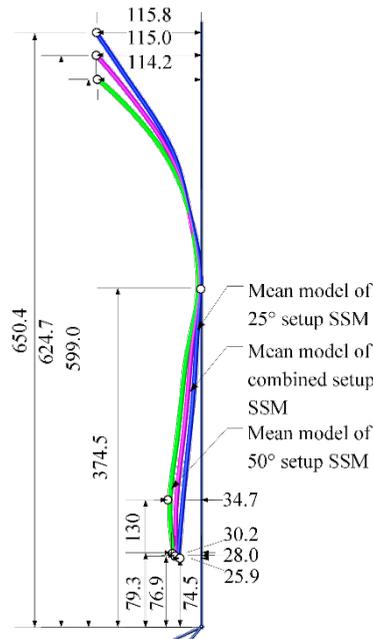
The second key question is: **What are the solutions that could be explored to improve these (dis)comfort factors in the selected mobility solutions? (KQ2)**

This question will be answered by using the articles in this dissertation which include possible solutions to improve future mobility. Attention was given to the acoustic comfort in turboprop aircrafts and sleeping in transit, like in a train, airplane, and car. The results are described under three headings: 'The human back contour for future non-driving related activities in automated vehicles', referring to chapter 3; 'Wearables for acoustic comfort improvement in a turboprop aircraft', referring to chapter 4; and 'Towards comfortable sleep on the road', referring to chapters 2, 3, and 4.

#### *The human back contour for future non-driving related activities in automated vehicles*

The interaction between the person and the seat is an important comfort influence. The shape of the backrest is the interface where the person and the seat interact. Previous research studied the backrest shape in an upright 'drivers' position. By adjusting the seat to the human back contour, the seat comfort was improved (Franz et al., 2011). In AVs and other mobility modes, non-driving related activities are possible. Chapter 3.3 studied the back contour of people while sitting in a seat with the backrest angles 115° and 140°, to improve ergonomic seat designs. The 115° backrest angle is comparable to the driver's position (Kilincsoy et al., 2014). Based on the findings, statistical shape models were generated for both backrest angles. In a seat back angle of 140° a more

pronounced curvature and more variability is observed compared to 115°. Variance in the back contour can mostly be explained by back height, neck bending, and lumbar variability. The outcomes of this article provide guidelines for backrest height adjustability, show the potential for an extra pivotal joint in backrest design to compensate for neck curvature, and show the importance of an adjustable lumbar support.



**Figure 5.3** 2D mean back contour models of the 115°, 140°, and combined setups, distance unit in mm (as presented in chapter 3.3).

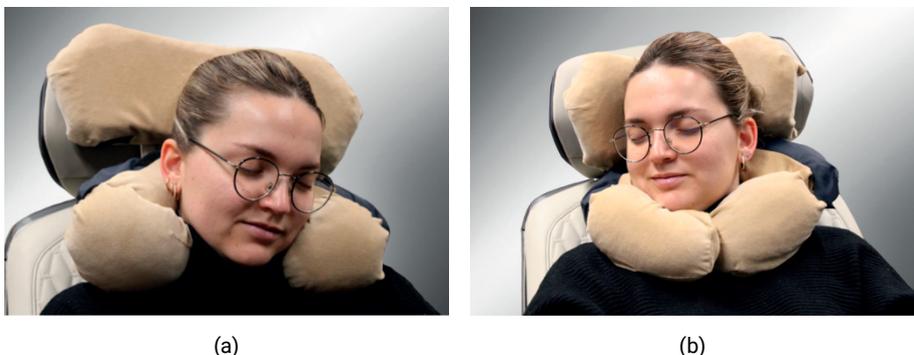
#### *Wearables for acoustic comfort improvement in a turboprop aircraft*

As was established in chapter 2.1, noise is a top factor for the development of discomfort in current propeller aircrafts. Chapter 4.1 assesses the effectiveness of active noise cancellation headphones (ANC) and earplugs to improve the comfort and discomfort experience of passengers in these propeller aircraft, and reduce the experienced noise. It is concluded that both ANC headphones and earplugs have a positive effect on passenger comfort and discomfort. There is a small preference for ANC headphones over earplugs, although this is not a significant difference. The use of ANC headphones and earplugs proves to be an effective method of improving the acoustic comfort and discomfort experience in turboprop airplanes (and future electric propeller airplanes), especially for the near future/current time. For far future scenarios it is interesting to search/consider more structural solutions such as ANC build into the seat (Dimino et al., 2022), ANC wall panels (Arena et al., 2017), better fuselage sound isolation,

or propeller synchrophasing (Chirico et al., 2018); alternatives that do not cause 'device specific' discomfort in the form of e.g. extra weight on the head, inner ear discomfort (as was discovered with the developed ELD (Ear Local Discomfort) question) or cause difficulty for communication and social activities.

#### *Towards comfortable sleep on the road*

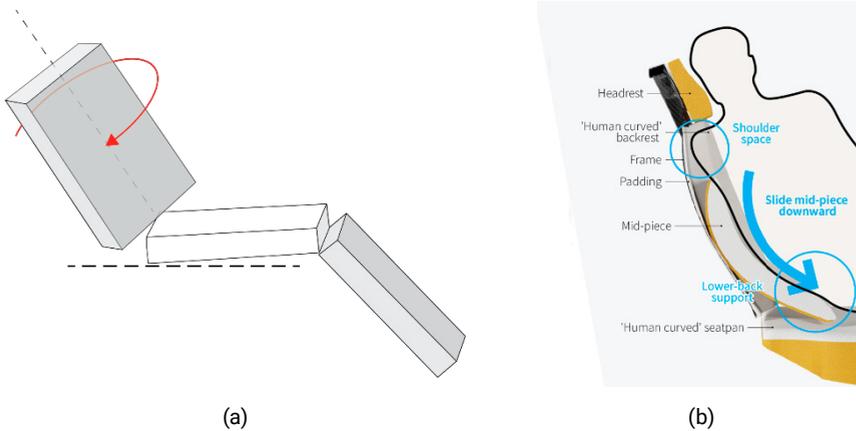
Within chapters 2.2, 3.2, and 4.2, several important comfort factors for comfortable sleep on the road were identified. Based on these comfort factors, it is possible to suggest certain design guidelines for people in industry, and suggest solutions that could be explored to further improve sleeping comfort in transit. A bed of 200 x 90 cm will facilitate all sleeping positions for the majority of people. If space is limited, during travel for one night, a bed size of 171 x 76 cm could suffice, as it allows for side sleeping, for most people it is a preferred sleeping posture (chapter 2.2). In an upright sleeping situation, a minimal angle of 130° is advisable for an acceptable comfort during a nap (Vledder et al., 2024). Chapter 3.2 describes that local discomfort in the areas of the neck, knees, lower legs, and feet deserves additional attention in seat design. A lack of neck support and uncomfortable feet/leg supports are explicitly mentioned. Especially a head support should be seen as a minimal requirement for facilitating an acceptable upright sleeping experience. The importance of the headrest is also confirmed in earlier studies (Bouwens et al., 2018; Vink et al., 2023). Possible solutions might be sought in designing a headrest that restricts the head from moving to the side, front, and back (Bouwens et al., 2018). **Figure 5.4** shows an example of a possible headrest solution.



**Figure 5.4** A headrest prototype preventing the head from side movement (a), and front movement (b) by placing something underneath the chin (Sabater Campomanes, 2024)

Furthermore, in chapter 3.2 the preference for side sleeping in reclined angles (rotated or leaning to the side with the torso), freedom of movement, and the impact of anthropometry on the sleeping posture are mentioned. Suggesting that facilitating upright sleeping should be given attention, to facilitating anthropometric variation (especially BMI and elbow to elbow width), by for instance introducing varying armrest widths. Also, the novel seating support

characteristic of a backrest roll angle (BRA) could be explored (**Fig. 5.5a**), or a seat that facilitates the shoulder shape in the backrest when people are sleeping sideways in a seat (**Fig. 5.5a**).



**Figure 5.5** Backrest roll angle (a), and shoulder space with lower back support facilitation (b) (Smulders, 2024)

As it was established earlier the impact of certain factors differs significantly across mobility modes. In addition to the previously mentioned comfort factors, privacy and security prove to be particularly important for comfort in sleeper trains (Heufke Kantelaar et al., 2022). Vledder et al. (2023) also mention the importance of privacy and security. Therefore, chapter 4.2 studied the feeling of privacy and security comfort needs in day and night trains through a VR case study with changing interior elements. Although this is a case study and additional research is necessary, the results show a tension field between privacy and security needs, and differences in these needs between day and night train travel. Perceived safety is influenced by proxemics to others, which can be influenced by adding separations between passengers or adding more space. Factors such as visual openness (supporting social control), enclosed compartments for storing belongings, or areas for isolation all play a role. However, the space must not be too small or closed, to avoid creating an oppressive atmosphere. Security is influenced by not being seen or heard in interaction with other passengers and therefore prefers a closed space or visual obstructions. Passengers' privacy and security requirements are generally higher during nighttime travel. Additionally, in this study, there were small differences found between men and women. Men value privacy and for instance, noise cancellation slightly more during the night, compared to women who find it more important to have an overview in the train to gain social control. These findings highlight the difficult puzzle for train interior designers, not only between privacy and security, but also between environmental and social requirements. For

example, acoustic or visual comfort has a contradicting need compared to safety if an open space is considered. **Figure 5.6** shows an example of a train interior design that took these findings into account and proposes one interior design that can be switched from day to night layout by the passengers themselves. This switch is important for train companies to improve the business case of night train services.

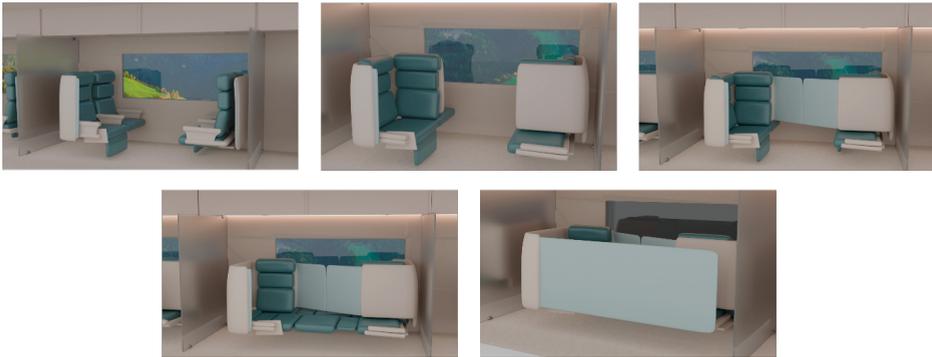


Figure 5.6. A day and night time compatible train interior (Out, 2024)

**Table 5.1** shows a comprehensive overview of the gathered requirements for a comfortable sleeping experience on the road as gathered throughout this dissertation and literature.

Table 5.1. Advised requirements for comfortable sleep during travel

| Requirement                                  | Amount   | Original source                                    |
|--|--|--|
| Jerk   | <0.2 m/s <sup>3</sup>  | (Kimura et al., 2017)                              |
| Temperature                                  | 17 – 28 °C   | (Caddick et al., 2018)                             |
| Humidity                                     | 40-60%   | (Caddick et al., 2018)                             |
| Sound  | < 35 or 55 dB(A)   | (Caddick et al., 2017)(Ozcan & Nemlioglu, 2006)    |
| Sound variations                             | < 5dB  | (Caddick et al., 2017)(Parnell & Wassermann, 2014) |
| CO <sub>2</sub>                              | 2582 ppm   | (Caddick et al., 2018)                             |
| Space dimensions in a flat bed for one night | ≥171 x 76 cm   | Chapter 2.2  |
| Seat backrest angle                          | ≥130°  | (Vledder et al., 2024) and chapter 3.2             |
| Privacy                                      | Visual and acoustic privacy, through closed spaces or spatial obstructions/divisions | Chapter 4.2  |
| Security                                     | Social control through semi-open spaces  | Chapter 4.2  |

### 5.3 Reflection on Methods and Limitations

#### *Methods measuring human experience and physical characteristics*

In studying comfort and discomfort, various methods were used in this dissertation. It might be worthwhile to reflect upon these to support future scientific studies and understand the value of the outcomes. Therefore, a reflection on methods is described in this chapter. **Table 5.2** shows a comprehensive list of the methods used in this dissertation. Within each research, it was attempted to study the experience of participants next to physical or physiological characteristics. Each serves its own purpose. Ideally, both measures verify the outcome or provide explanations for the results. Although preferably, using both is not always possible. Which is especially true for sleep research, as was also mentioned by Smulders (2024, p. 224). Polysomnography (PSG), the industry standard to measure sleep in sleep time, sleep stages, and sleep fragmentation, was not available for the research in this dissertation. Additionally, this method is intrusive; it limits freedom of movement and therefore restricts natural behaviour. The downside is that directly linking sleep quality to (dis)comfort is much harder and relies more heavily on standardized sleep questionnaires such as the Pittsburgh Sleep Quality Index questionnaires or the Karolinska Sleepiness Scale. This could also be seen as an extra motivation to search for alternatives, which is exemplary of the problem-solving mindset rooted in research within the Industrial Design Engineering

faculty and therefore in this PhD thesis as well. Alternatively, it was attempted to link sleep comfort to sleeping postures and movement frequency (successful) (chapter 2.2, and 3.2), and to reaction speed (PVT)(unsuccessful)(chapter 3.2). Within the research group, this was just the beginning of a creative search and development of objective data methods. Follow-up studies might include optimized body skeleton tracking for an automated posture and movement analysis, the measurement of skin temperature and electrodermal activity (EDA) to link the emotional state to comfort, or the tracking of eye blinking linked to sleepiness. With an optimized body skeleton, it might be possible to link the depth of sleep to motility in upright sleeping (Bader & Engdal, 2000). This remains an ongoing process, and although these methods cannot replace PSG, it does show the possibilities to create scientifically relevant results when a creative and flexible attitude is adopted without loss of quality. Based on the experience within this PhD thesis, it could be seen as a recommendation to other PhD candidates (and other researchers) to adopt this mindset.

The list of methods provided includes some that were not ultimately presented in the final publications. In most cases, the data gathered from these “unpublished” methods either did not reveal significant differences or proved difficult to interpret. However, it is often challenging to predict in advance which methods will yield valuable or usable data, an uncertainty that is inherent to the nature of scientific research. Not all methods lead to meaningful or publishable results, but they are nonetheless included here for transparency and completeness.

Table 5.2: methods used in this dissertation

| <b>Method</b>   | <b>Chapter</b> |
|---|----------------|
| Interviews  | 4.2, 2.3       |
| Questionnaires  | All chapters   |
| - Open questions  |                |
| - Likert scale (dis)comfort   |                |
| - Ranking (dis)comfort factors or other rankings  |                |
| - Local Perceived Discomfort (LPD)  |                |
| - Ear Local Discomfort questionnaire (ELD)  |                |
| - Pittsburg Sleep Quality Index questionnaires (PSQI)   |                |
| - Acoustical environment questionnaire (ISO 28802:2012)*  |                |
| - Karolinska Sleepiness Scale (KSS)*  |                |
| - Samn-Perelli 7-point Fatigue Scale (SPFS)*  |                |
| Observations  | 2.2, 3.2       |
| Posture analysis  | 2.2, 3.2       |
| Movement analysis   | 3.2            |
| Anthropometric measurements   | All chapters   |
| Surface area measurements   | 2.2            |
| Sound dB(A) meter   | 4.1            |
| Temperature   | 3.2*, 4.1*     |
| Humidity  | 3.2*, 4.1*     |
| CO <sub>2</sub>   | 3.2*, 4.1*     |
| VR simulations  | 4.2            |
| Psychomotor Vigilance Test (PVT)*   | 3.2            |
| Heart Rate Variability (HRV)*   | 4.1            |
| Back contour measurement (digital kyphometer)   | 3.3            |
| Recording participants movement, local temperature, light and CO <sub>2</sub> (Yao et al., 2023)* | 4.1*           |

*\*Method used, but results are not included in the publication*

### *Lab vs. real world*

Within this PhD thesis, most studies are lab studies (except the study in chapter 2.1, and chapter 2.2 to some extent). The use of the lab as a testing location allows creating a controlled environment but can also impose limitations. In the real world, the movement and vibration of a vehicle can wake people, but can also rock them to sleep (Vledder et al., 2023); vibration can have an amplifying effect on the experience of noise (Aggarwal et al., 2022), or people can prefer a less reclined backrest angle in an actual driving vehicle because of the need to be aware of the traffic and the feeling of control, in case people are not trusting the AV completely yet (Makris et al., 2025). A certain amount of vibration or movement might be added to a lab environment, but unexpected influences such as those mentioned by Makris et al. (2025) cannot always be modelled. This was also mentioned by Yao (2023, p. 93), who additionally pointed out the potential of mixed reality as a tangible prototyping tool, as used in chapter 4.2 of this dissertation, but Yao also emphasizes the risk of a low-fidelity prototype. Therefore, the next step in sleep research might be to leave the lab setting and/or increase the simulation reality.

### *Participant inclusivity and the facilitation to make this happen*

Without the loss of relevance to the work in this dissertation, it would serve to have a critical look at the use of a limited age group within most studies that are included in this dissertation. Except the studies included in chapters 2.1 and 2.2, the other studies heavily relied on the use of participants in a very limited age group, the readily available student population. It is a limitation mentioned in each article separately and might be acceptable within the framework of those articles, but eventually, the impact of this limitation might be more important than expected. The generalizability of the results is certainly influenced by this choice. Whether it is acceptable or not should be discussed within the framework of inclusive research and innovation (IRI), from an ethical perspective, and within the specific research question. Although the compromises cannot be seen separate from the available resources and time available within this PhD thesis. There should have been more awareness of the possible implications. Sleep positions in cars might seem harmless, but as researchers, we have no control over how our results will be used. If these results were used in future crash testing, however far-fetched, the safety implications are unknown. In this context, examples of non-inclusive research and development and their impact are readily available. The use of the average male as a norm in vehicle crash testing, which leads to a higher injury risk for female drivers and passengers, is a well-known example (Linder & Svensson, 2019).

In chapter 2.2 of this dissertation a creative solution was sought; student participants were stimulated to invite their parents into the study, but this might

not always be possible. In general it takes extensive effort and dedication from the researchers to search for fitting test subjects outside the student population. Possibly within this PhD thesis more effort should have been made to reach a bigger group, but it cannot be attributed to a lack of willingness. The role of the context should be discussed related to this topic as there is a certain time frame, there is no system to easily recruit different types of participants, and within the university system, there is a limited support structure. Besides age, the use of the student population also leads to loss of important insights in other fields, e.g., socio-economic backgrounds, world views, cultures, etc. Therefore, it might serve the university to show initiative in the creation of a platform to support staff and students in connecting them to specific user groups. A few local initiatives within research labs are known (*IBEX-Lab | Behavioral Research @TUD*, n.d.), showing the possible extent of the issue within the university.

*Practical suggestions based on experience obtained from this PhD thesis*

Based on experience obtained in this PhD thesis, some practical suggestions are formulated for future research.

Firstly, when planning a sleep study during daytime some factors should be considered. As discussed in this dissertation (Chapters 2.2, 3.2, and 4.2), facilitating sleep requires several environmental conditions. These include a dark and quiet environment, the exclusion of snoring participants when multiple people are sleeping in the same room, proper setup and positioning of cameras, and the use of a separate control room. Whether these conditions can be met should be actively assessed through a pilot test before the study begins. Additionally, communication with building facility management should be higher on the priority list so that, for instance, automatic lighting can be disabled, and accidental disruptions of sleep by switching on the light or people entering the room can be avoided.

Secondly, when organizing a large study involving around 100 participants, facility contingency plans for several worst-case scenarios should be made. For instance, in the study that included a real test flight (chapter 2.1), before going into the airplane the participants would be received in a special terminal at the airport, but the possibility of the local soccer team (Feyenoord) claiming the terminal for their travel at the local airport was not considered. In a very late stage, the research team had to improvise and do their best to find an alternative solution.

Thirdly, a practical tip for future observations will be to first test posture classifications on a limited dataset to avoid the generation of unnecessary work for all researchers involved in case the classifications are not adequate. In the

case described in our study (chapter 3.2), observations had to be redone as the first classification was not working sufficiently.

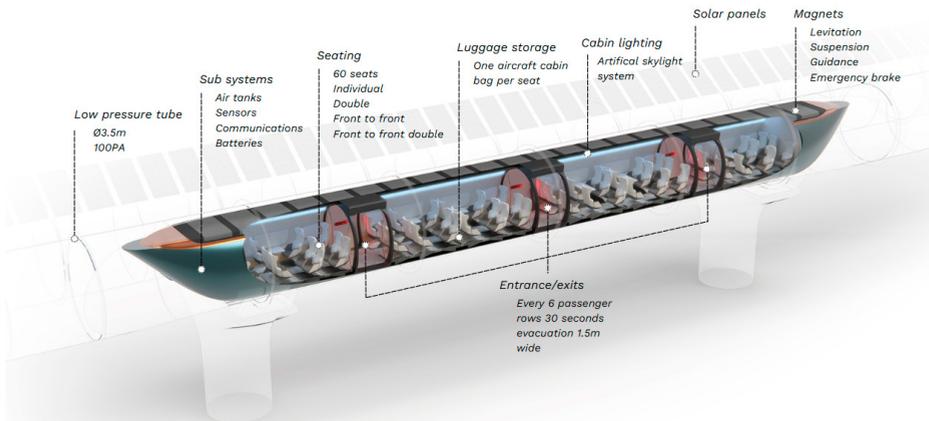
Fourthly, it is wise to more precisely define the sitting posture of participants before the study. In the study where the contour of the back rest was determined (chapter 3.3), in the 115° backrest angle setup participants were asked to look at a point in front of them comparable to a driving posture (flexed neck). In the 140° backrest angle setup the participants were let free to position their head relaxed, which could include looking forward, or could include laying the head down for sleeping (extended neck). However, after the experiment, it was concluded that choosing one position (sleeping or driving) could have been better, as repeating the experiment would be easier and there might be less variation in the results.

Finally, at the start of this dissertation, data analysis was mainly conducted through the use of the software SPSS, but after a few studies, the step was made to use the programming language Python for all data analysis steps. The great advantage of this switch was the ease with which certain analyses or statistical tests could be repeated with different data or with slightly different tests. Additionally, Python integrates more programming functionalities and is easier to use for visualizations. Therefore, the tip for future researchers would be to start using Python from the start of the dissertation, not only for statistical tests but for anything involving data analysis, from data preparation, data interpretation, to visualizations. The speed at which certain statistical tests can be done in Python opens the possibility to analyse more than previously possible within the same amount of time, but it also introduces the risk of over-analysis and the loss of oversight. The lesson learned using this approach is to always clearly keep the predefined research questions in mind and avoid certain biases that might occur when doing data analysis (e.g., cherry picking, confirmation bias, type one errors, post-hoc rationalization, etc.).

## 5.4 Considerations for Future Research

Although this dissertation provides new insights for future mobility solutions, mobility solutions are constantly changing, and the balance of comfort requirements continuously needs to be reconsidered and reevaluated. Automated driving is already a reality, but only in a small part of the world (Bhuiyan, 2023). As the technology matures and people get used to this form of travel, the way people perceive their comfort in these vehicles might change. Many studies in mobility rely on past experiences with a transportation mode. When more people have experienced AVs in the future, this might lead to new and interesting insights. For instance, will vehicle sharing services become more common, or will people still own a private car? As suggested in the Mobilizers

report (Mobilizers, 2025), a future research question might be: ‘How can we increase the user adoption of new emerging sustainable transportation modes, such as shared automated vehicles?’. Additionally, completely new transport modes might also be introduced. For instance, the hyperloop is a transportation mode that cannot be compared to other solutions that are currently in use (**Fig. 5.7**). The hyperloop development program expects that by 2040, the first commercially viable hyperloop lines can be realized (*Hyperloop, Accelerating Progress towards Europe’s Goal of Sustainable Transport, 2024*). The further development of the hyperloop will introduce an entirely new (dis)comfort research field. Opening up questions like how will passengers experience cornering in a hyperloop when it travels at a speed between 500-1000km/h? And Finally, a new way of traveling by airplane might be the Flying V (Liu et al., 2021), or windowless airplanes (Moruzzi et al., 2021). At this moment, these ways of travel might hold positive and negative expectations. The effects on comfort during a real flight in these airplanes are still unknown, and participants might also need to get used to them.



**Figure 5.7** An example of what the hyperloop system can look like (Hardt Hyperloop, n.d.)

In this dissertation, it was defined that besides the seat, and in vehicle noise, vehicle movement (especially in a car) has a big influence on in-vehicle sleep (chapter 2.2). This shows there is an opportunity for future research to further define the influence of vehicle movement and vibration on sleep comfort, sleep quality, sleep onset, and sleep postures.

Future research could also explore cultural differences in sleeping habits and how these will influence the way people want to sleep during transit. Although the constructs of comfort and discomfort mean similar things in different countries, differences between comfort experiences of products are not

uncommon, especially for products related to sleep (Vink et al., 2021). Sleep habits, e.g., the place where we sleep and how long we sleep, are culturally dependent. In North America and northern Europe it is most common to have one major nighttime sleep period, while in for instance Spain a large nocturnal sleep period is combined with a shorter sleep during midday (siesta), and in Japan or India shorter naps are common and more depending on the degree of sleepiness and the opportunity to sleep (Krahn, 2010). Although, because of a globalized economy, cultural differences might become smaller, this might influence the likelihood of taking short naps in a vehicle in some cultural settings. Additionally, while in Europe we usually sleep in a bed with a mattress, in some countries it might be common to roll out a mat or mattress on the floor each night, and others sleep in hammocks (Flaskerud, 2015). **Figure 5.8** shows the sleeping environment of a child somewhere in India. This shows the importance of including a cultural perspective in future in-vehicle sleep research, especially since sleep surfaces also influence sleeping postures. In China, most people sleep on their backs, while in Europe most people sleep on their sides (Chen et al., 2013). As a result, people who e.g., prefer sleeping prone or laterally can experience less sleep quality in a sagging bed (Verhaert et al., 2011), and therefore have different sleep surface preferences. But it is also known that sleeping habits and preferences can change over time, for instance, the habit of sleeping upright in a reclined position of people in the UK and the Netherlands was quite normal during the Middle Ages (*De Geschiedenis van Het Slaapcomfort*, n.d.; Yuko, 2021). Even though they did this because of superstition and to aid digestion, and not for comfort reasons, it does show that sleep environments and habits can change. In a more recent example, the introduction of a round 'body pillow' between the legs increased lateral sleeping duration (**Fig. 5.9**) (Park et al., 2021). Even though there is a habituation effect of supported pressure on specific body parts during sleep (Bader & Engdal, 2000). The pillow example suggests that sleep postures can be designed for.



Figure 5.8 A child's bedroom in India (Mollison, 2023)

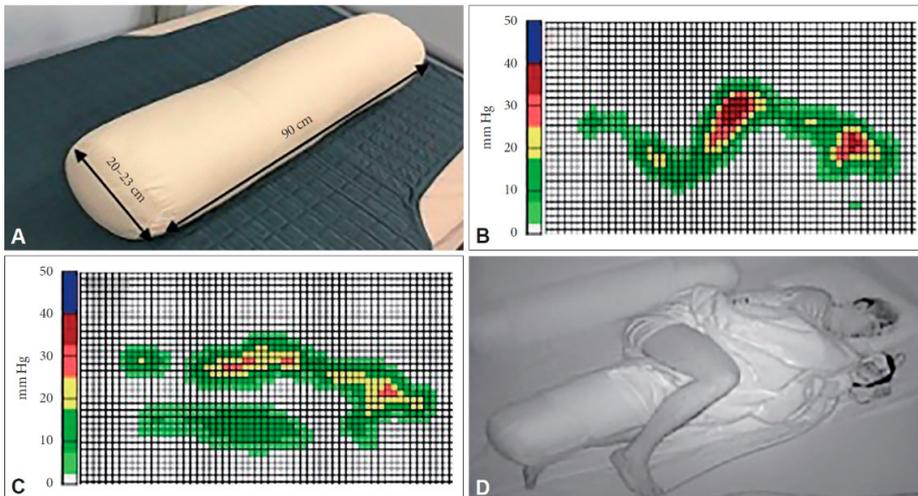


Figure 5.9 The 'body pillow' and a picture of the pressure distribution with and without the body pillow (Park et al., 2021)

Finally, the comfort aspect was central in the study on the ideal backrest angle and upright sleeping postures (chapter 3.2). Therefore, safety issues were not extensively studied. It is recognized that in a reclined seat, the risk of sliding underneath the lap belt is increased (submarining) (Grébonval et al., 2021; Singh, 2023), adding to the injury risk in a driving vehicle. This shows the need to further study possible safety implications of a changing seat posture in a driving vehicle. Additionally, Górnaiak et al. (2022) studied head-related injuries and whiplash in reclined seats using a 50th percentile anthropomorphic test dummy (ATD). This

study compared different seat angles and crash pulses and found that greater seat inclinations, particularly around 130°, led to a lower risk of head injuries. However, fully reclined seats exhibited the highest head accelerations. Injury risk is not the topic of this dissertation, but it certainly needs attention when a wider range of backrest angles becomes available in a driving car.

## 5.5 Conclusion

This dissertation has explored comfort in the evolving landscape of mobility, guided by the central research question: How can the passenger (dis)comfort experience be improved in future mobility solutions? This question was addressed through two key sub-questions. KQ1: What are the (dis)comfort factors that need to be improved? focused on identifying and understanding the relevant comfort factors across various transport modes. KQ2: What are the solutions that could be explored to improve these (dis)comfort factors in selected mobility solutions? emphasized the exploration of interventions and design strategies. The investigation highlights major mobility trends such as the growing adoption of turboprop and electric aircraft, the emergence of autonomous vehicles, and the renewed interest in sleeper trains, all of which present both challenges and opportunities for enhancing passenger comfort.

In propeller-driven aircraft, noise remains a key discomfort factor. This dissertation demonstrates the effectiveness of simple solutions such as noise-cancelling headphones and earplugs, and also points to more innovative possibilities like integrated active noise cancellation within the aircraft seat. With the rise of self-driving cars, occupants, formerly drivers, are expected to engage in more non-driving-related activities (NDRAs), such as resting or sleeping. This research provides evidence-based recommendations on optimal backrest angles and insights into sleeping postures and sleep movement in upright sleeping to support these activities. It also offers broader guidance on sleep accommodations in various transport contexts, including both flat-bed and seated configurations, while addressing critical environmental factors such as lighting, noise, temperature, privacy, and security in sleeping during transit.

As mobility technologies continue to evolve, further research, particularly in real-world settings with diverse populations, is essential. Much of the current work was conducted under controlled laboratory conditions with student participants, which limits the generalizability of the findings. Future studies should therefore focus on validating these insights in operational transport environments, involving a broader demographic of users, examining long-term comfort experiences across full journey durations, and continuously adapting to the changing context of mobility.

## 5.6 References

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## About the Author



Gerbera Vledder was born on the 4<sup>th</sup> of January 1993 in Kempton Park, South Africa. In 2011, Gerbera completed her secondary education at Emmaus College in Rotterdam, after which she continued with a bachelor's degree in Industrial Design Engineering at the Delft University of Technology, followed by a master's degree in Integrated Product Design at the same university. She finished her master's in 2017 with the thesis titled: 'Redesign of a business class armrest: Improvement of arm comfort for watching in-flight entertainment and reading' in collaboration with RECARO aircraft seating.

After graduation, Gerbera worked as a design engineer in BYD Europe, working on fully electric city bus interior and exterior design for the European market. In 2021, she rejoined the academic world in pursuit of a PhD at the Faculty of Industrial Design Engineering, Delft University of Technology. During her research, she focused her work on improving passenger comfort in sustainable future transport modes, including, among others, a psychoacoustic and biomechanical perspective. During this time, she also participated in design education by coaching several student groups in the course 'Advanced Embodiment Design' and guided five master graduate students in their thesis projects, which she all greatly enjoyed. During her PhD Gerbera also spend 4 months at the Gustave Eiffel University in Lyon, France where she conducted research together with local scientists. Her work also involved European collaboration within the H2020 COMFDEMO European project and collaboration with many industry partners such as BMW, Elysian aircraft, JLR, Embraer, and Royal Haskoning DHV.

In September 2025, Gerbera continued in academics with a postdoctoral position in 'Human Centred Design for Smart Mobility'.

## List of Publications

Publications Part of This Thesis

### Chapter 2: Environment

3. Vink, P., Vledder, G., Song, Y., Herbig, B., Reichherzer, A. S., & Mansfield, N. (2022). Aircraft interior and seat design: priorities based on passengers' opinions. *International Journal of Aviation, Aeronautics, and Aerospace*, 9(1). <https://doi.org/10.15394/ijaaa.2022.1679>
4. Vink, P., Vledder, G., Smulders, M., & Song, Y. (2025). How do we sleep? Towards physical requirements for space and environment while travelling. *Applied Ergonomics*, 122. <https://doi.org/10.1016/j.apergo.2024.104386>

### Chapter 3: Person

4. Kılıç, H., Vledder, G., Yao, X., Elkhuisen, W. S., Song, Y., & Vink, P. (2023). Recruiting participants for ergonomic research using self-reported stature and body mass. *WORK: A Journal of Prevention, Assessment & Rehabilitation*, 76(4), 1509–1517. <https://doi.org/10.3233/WOR-220565>
5. Vledder, G., Singh, U., Sabater Compomanes, R., Kılıç, H., Smulders, M., Song, Y., Vink, P. (Manuscript submitted for publication) Impact of Seat Back Recline Angles on Sleeping Posture and Perceived Sleeping Comfort. *Applied Ergonomics*.
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