



Delft University of Technology

Document Version

Final published version

Citation (APA)

Smulders, M. (2024). *Seating and sleeping comfort in transit: Recommendations on human activity-based research and design for vehicle seats*. [Dissertation (TU Delft), Delft University of Technology]. <https://doi.org/10.4233/uuid:5f757366-8eb4-492a-9e69-56950277c82f>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

In case the licence states "Dutch Copyright Act (Article 25fa)", this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.
Unless copyright is transferred by contract or statute, it remains with the copyright holder.

Sharing and reuse

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.

Seating and sleeping comfort in transit

Recommendations on human activity-based research and design for vehicle seats



Maxim Smulders

Seating and sleeping comfort in transit

Recommendations on human activity-based research and design for vehicle seats

Dissertation

for the purpose of obtaining the degree of doctor
at the 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 18 September 2024 at 15:00 o'clock

by
Maxim Smulders
Master of Science in Industrial Design Engineering,
Delft University of Technology, The Netherlands
born in Delft, The Netherlands

This dissertation has been approved by the promotor.

Composition of the doctoral committee:

Rector Magnificus	Chair
Prof.dr. P. Vink	Technische Universiteit Delft, promotor
Dr. Y. Song	Technische Universiteit Delft, promotor

Independent members:

Prof.dr.mr.ir. S.C. Santema	Technische Universiteit Delft, The Netherlands
Dr.ir. M. Melles	Technische Universiteit Delft, The Netherlands
Prof.dr. N.J. Mansfield	Nottingham Trent University, United Kingdom
Prof.dr. A. Naddeo	University of Salerno, Italy
Dr.ir. S. Hiemstra-van Mastrigt	Technische Universiteit Delft, The Netherlands

Reserve member:

Prof.dr.ir. R. Happee	Technische Universiteit Delft, The Netherlands
-----------------------	--

This research has partly been funded by BMW Group AG, Safran Group SA, Vanema Storitve d.o.o., and the Dutch Research Council (NWO) (project number: 18636).

**BMW
GROUP**

 **SAFRAN**
vanema.



Keywords: aircraft, bed, bunk, bus, car, comfort, IFE, IVE, seat, ship, sleep, train

Proofreading: Dolores Hilhorst

Graphic design: Maxim Smulders

Print: Printplezier (formerly Druk. Tan Heck; in memory of Ton van de Nieuwenhuijzen)

ISBN 978-94-6384-640-0

An electronic copy of this dissertation is available at www.repository.tudelft.nl

© 2024 Maxim Smulders

All rights reserved. No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage or retrieval system, without permission from the author.

Seating and sleeping comfort in transit

Recommendations on human activity-based research and design for vehicle seats

To my parents.

In memory of W.M.T. Smulders-Mokveld.

CONTENTS

English summary	13
Nederlandse samenvatting	15
1 General introduction	19
1.1. Background on interior design for transit	20
1.1.1. Push for change	20
1.1.2. Human activities in transit.....	21
1.2. The challenge of designing for long-distance travel: balancing seating and sleeping comfort against economics and operational safety	22
1.2.1. The (dis)comfort of long-distance travel	23
1.2.2. Entertainment in transit.....	23
1.2.3. Sleeping in transit	23
1.2.4. Scientific gap.....	24
1.3. Aim of this dissertation.....	24
1.3.1. Research questions.....	25
1.4. Dissertation outline.....	26
1.4.1. Part 1: (Dis)comfort and human behaviour.....	27
1.4.2. Part 2: Design for seating in transit based on the human contour.....	27
1.4.3. Part 3: Design for full-flat sleep in transit.....	27
1.4.4. Part 4: Design for entertainment and reclined sleeping in transit.....	28
1.4.5. Chapter 11: General discussion and conclusion.....	28
1.5. References.....	30
PART 1 (DIS)COMFORT AND HUMAN BEHAVIOUR	37
2 Human behaviour should be recorded in (dis)comfort research	39
2.1. Introduction.....	41
2.2. Theoretical explanation	42
2.2.1. Context and activity versus (dis)comfort.....	43
2.2.2. Posture versus (dis)comfort	43
2.2.3. Movement versus (dis)comfort.....	44

2.2.4.	Previous conditions and expectations versus (dis)comfort	45
2.2.5.	(Distracting) stimuli versus (dis)comfort	45
2.2.6.	Time versus (dis)comfort.....	47
2.3.	Conclusion	48
2.4.	Acknowledgements.....	48
2.5.	References	48
3	Comfort and discomfort effects over time: the sweetness of discomfort and the pleasure towards the end.....	53
3.1.	Introduction	55
3.2.	Methods	57
3.3.	Results and discussion.....	57
3.4.	Conclusion	61
3.5.	References	62
PART 2	DESIGN FOR SEATING IN TRANSIT	65
4	Comfort and pressure distribution in a human contour shaped aircraft seat (developed with 3D scans of the human body).....	67
4.1.	Introduction to human contoured seating.....	69
4.2.	Materials and methods	70
4.2.1.	Inclination for different activities in Business Class aircraft seats.....	70
4.2.2.	3D scanning the human contour in pre-determined inclinations	73
4.2.3.	Pressure distribution calculations and testing for cushioning	77
4.2.4.	Prototyping business aircraft seat based on the human contour.....	80
4.2.5.	Comfort and discomfort effects of the prototype and traditional seat.....	80
4.2.6.	Pressure distribution effects of the prototype and traditional seat.....	83
4.3.	Results	84
4.3.1.	Inclination for different activities in Business Class aircraft seats.....	84
4.3.2.	3D scanning the human contour in pre-determined inclinations	85
4.3.3.	Pressure distribution calculations and testing	86
4.3.4.	Prototyping business aircraft seat based on the human contour.....	87
4.3.5.	Comfort and discomfort effects of the prototype and traditional seat.....	87
4.3.6.	Pressure distribution effects of the prototype and traditional seat.....	89

4.4.	Discussion	89
4.4.1.	Inclination for different activities in Business Class aircraft seats	89
4.4.2.	3D scanning the human contour in pre-determined inclinations.....	89
4.4.3.	Pressure distribution calculations and testing.....	90
4.4.4.	Prototyping business aircraft seat based on the human contour	91
4.4.5.	Comfort and discomfort effects of the prototype and traditional seat	91
4.4.6.	Pressure distribution effects of the prototype and traditional seat	91
4.5.	Conclusion	92
4.6.	Acknowledgements	92
4.7.	References.....	93
5	Designing aircraft seats to fit the human body contour	97
5.1.	Introduction to human body contour seat design	99
5.2.	Method of acquiring the human body contour through indirect 3D scanning	99
5.2.1.	Participants.....	99
5.2.2.	Setup and procedure.....	100
5.2.3.	Data processing	102
5.3.	Results and application of 3D scans.....	104
5.3.1.	Adjustable seat pan feature for economy class seat	104
5.3.2.	Lateral sleeping design concept for premium economy class seat	105
5.3.3.	Full-flat sleeping design concept for business class seat.....	105
5.4.	Discussion and recommendations on designing aircraft seats to fit the human body contour	106
5.5.	Conclusion	108
5.6.	Acknowledgements	109
5.7.	References.....	109
6	Implementing foam spring technology to design a light weight and comfortable aircraft seat pan	113
6.1.	Introduction.....	115
6.1.1.	Ideal pressure distribution	116
6.1.2.	Ideal contour	117
6.1.3.	Cushioning firmness	117

6.1.4.	Foam spring seat cushion design.....	118
6.2.	Method and materials.....	119
6.2.1.	Study setup.....	119
6.2.2.	Participants.....	121
6.2.3.	Procedure.....	121
6.2.4.	Measurements.....	122
6.3.	Results and discussion.....	124
6.3.1.	Local perceived discomfort.....	124
6.3.2.	Overall perceived discomfort.....	124
6.3.3.	Overall perceived comfort.....	124
6.3.4.	Cushioning firmness.....	125
6.3.5.	Seat preference and user remarks.....	126
6.3.6.	Pressure distribution.....	126
6.3.7.	Cushion weight reduction.....	128
6.3.8.	Study limitations.....	128
6.3.9.	Future design improvement and research.....	129
6.4.	Conclusion.....	130
6.5.	Ethical approval.....	130
6.6.	Declaration of competing interest.....	130
6.7.	Acknowledgements.....	130
6.8.	References.....	131

PART 3 DESIGN FOR FULL-FLAT SLEEP IN TRANSIT135

7	Sleeping postures in adults: a literature exploration	137
7.1.	Introduction.....	139
7.2.	Method.....	139
7.3.	Results.....	140
7.4.	Discussion.....	142
7.5.	Conclusion.....	143
7.6.	References.....	144

8	Sleep quality and (dis)comfort in a minimal space envelope	147
8.1.	Introduction.....	149
8.2.	Method.....	149
8.3.	Results.....	152
8.4.	Discussion	154
8.5.	Conclusion	155
8.6.	Ethical approval	155
8.7.	References.....	156
9	Neck posture and muscle activity in a reclined business class aircraft seat watching IFE with and without head support	161
9.1.	Introduction.....	164
9.1.1.	Preference for a slouched posture when watching IFE/TV	164
9.1.2.	Head flexion and the strain on the muscles.....	167
9.1.3.	Theoretical biomechanical simulation.....	169
9.2.	Materials and methods.....	170
9.2.1.	Participants.....	170
9.2.2.	Experimental setup and stimuli.....	171
9.2.3.	Apparatus.....	174
9.2.4.	Procedure	174
9.2.5.	Measures	176
9.3.	Results.....	178
9.4.	Discussion	180
9.4.1.	Muscle activity and fatigue	180
9.4.2.	Expected long-term comfort	181
9.4.3.	Posture	181
9.4.4.	Study limitations and suggestions.....	182
9.5.	Conclusion	183
9.5.1.	Relevance for the industry.....	183
9.6.	Conflicts of interest	183
9.7.	Acknowledgements	183
9.8.	References.....	184

10	Dense 3D pressure discomfort threshold (PDT) map of the human head, face and neck: A new method for mapping human sensitivity	191
10.1.	Introduction	193
10.2.	Participants, materials and method.....	194
10.2.1.	Participants	194
10.2.2.	Apparatus	194
10.2.3.	Procedure.....	196
10.2.4.	Measures.....	197
10.3.	Results	199
10.3.1.	Average PDT map.....	199
10.3.2.	PDT gender difference	203
10.3.3.	PDT zone difference	203
10.4.	Discussion	205
10.4.1.	Underlying tissue.....	206
10.4.2.	Differences between genders.....	206
10.4.3.	Design implications.....	207
10.4.4.	Limitations and suggestions for further research.....	208
10.5.	Conclusion	210
10.6.	Open data access.....	211
10.7.	Ethical approval.....	211
10.8.	Declaration of competing interest.....	211
10.9.	Acknowledgements.....	212
10.10.	References	213
11	General discussion and conclusion	219
11.1.	Overview of the results linked to the research questions.....	220
11.2.	Reflection on focus and methodology	222
11.2.1.	Objective methods	222
11.2.2.	Subjective methods	223
11.2.3.	Recommendation on methods for (dis)comfort research.....	224
11.3.	Recommendations for further research based on this dissertation	224
11.4.	Recommendations for future research beyond this dissertation	228
11.4.1.	Seating research recommendations.....	228

11.4.2.	Sleep research recommendations.....	230
11.5.	Recommendations for industry based on this dissertation.....	235
11.5.1.	Designing light weight seats based on the human contour	236
11.5.2.	Design for human activity.....	236
11.5.3.	Design for comfort over time	237
11.5.4.	Design for IVE/IFE	237
11.5.5.	Design for sleeping in transit.....	238
11.6.	Final statement: to conclude this doctoral dissertation.....	239
11.7.	References.....	240
	Acknowledgements.....	249
	About the author.....	251
	List of publications	254

ENGLISH SUMMARY

The interior of vehicles will change due to technological progress, a sustainability push and (related) changing user behaviour. Vehicle interiors will need to be more light weight to reduce energy consumption, while still providing the same level of comfort. Globalisation and new trends like automated driving, new propulsion methods in aviation and a push towards (long-distance and sleeper) trains ask for new interior designs. These new interiors should facilitate being productive in transit, relaxing and sleeping.

This doctoral dissertation aims to provide design guidelines or suggestions for designers and engineers to aid them in designing comfortable and useful seating and sleeping environments in vehicles (e.g. trains, aircraft, (automated) cars, ships, and submarines).

In (dis)comfort research, human activities and the effect of time should be taken into account (Part 1). In (dis)comfort research it is important to indicate what participants did before participating in the test (prior activities), how they move/behave during the test, what postures they assume, whether there are stimuli used that distract or influence the behaviour, and whether participants are aware of time or the end/duration of activities/stimuli (Chapter 2). It is also shown how time impacts (dis)comfort experience, where discomfort tends to stabilise or decrease and comfort tends to stabilise or increase towards the end. Participants being aware of time may impact (dis)comfort rating (Chapter 3).

One way to design comfortable light weight seats is to base them on the human contour (Part 2). The human contour can be derived from 3D scans and defines where material can be reduced. A human contoured seat does not impact (dis)comfort significantly compared to a traditional seat (Chapter 4). It allows for seat weight and seat volume reduction, which was shown for a business class, premium economy, and economy class aircraft seat (Chapter 5). By combining optimisation of pressure distribution, the use of porous materials (e.g. foam springs or weaved meshes) and topology optimised structures it is possible to reduce weight and at the same time increase comfort (Chapter 4 and 6). Obtaining a similar or more favourable comfort rating and a lower weight is beneficial to reduce environmental impact, which is relevant for future vehicle interior design (as discussed in the introduction).

The activity that most long-haul passengers rate as most important, but often experience as difficult, is sleeping (Part 3). Part 3 studies people sleeping in a full-flat position. Where healthy people need to be able to freely move during sleep, limiting space in vehicles influences sleep quality, efficiency and comfort. Although lateral and supine postures are dominant, seat-bed designs in vehicles should allow for postural changes and micromovements to facilitate natural sleep behaviour (Chapter 7). The sleeping space envelope can be reduced, but negatively impacts sleep quality and

comfort. This dissertation shows that with a space reduction of ~25% the sleep quality, efficiency and comfort seem quite acceptable (Chapter 8). However, it is up to designers and engineers to consciously balance sleep space envelope and sleep quality, sleep efficiency and comfort against other requirements like economics (e.g. volume and weight, and their impact on fuel consumption) and operational safety.

Another common relaxing activity is watching in-vehicle entertainment (IVE) on a screen, and napping/sleeping in a reclined seat (Part 4). As people tend to prefer a slouched posture for watching IVE, they often lack adequate support for the head and neck. Such head support by a headrest is more comfortable, but does not lower muscle activity (based on EMG data). A possible reason for this is that people tend to look for a neutral posture with minimal muscle activity (Chapter 9). To aid designers, engineers and scientists in designing headrests for IVE and reclined sleeping, a head sensitivity model was developed (which can also be used for other industries and applications, like face masks, glasses and headphones). This model shows that high pressures should be avoided around the ear, temple and neck area, where most of the load of the head can be carried by a headrest on the back of the head and the jaw line (Chapter 10).

The main research question of this doctoral dissertation was: *What are the physical ergonomic factors that influence seating comfort, relaxing comfort and sleeping quality and comfort?* The studies published in this doctoral dissertation show that physical factors have influence on seating, relaxing and sleeping comfort and sleep quality. In general, cases in this doctoral dissertation show that taking the human contour, the human sensitivity and human behaviour and time into account can lead to more comfortable, effective and potentially safer seating and sleeping environments in vehicles. Existing literature, as discussed in the chapters, supports these conclusions. In many cases, further research is needed to arrive at more substantiated and detailed guidelines for industry and science, especially for design for sleeping in transit.

As shown in this doctoral dissertation, seat design should be activity based, to accommodate natural behaviour, posture variation and in-seat movement, as these impact user (dis)comfort. Human contoured seating can improve seating comfort and reduce weight. Although sleep ergonomics has some attention in science, it is surprising how limited the scientific field on sleep ergonomics is developed. Although a first step has been made in this doctoral dissertation, more attention should be given to sleep ergonomics as this is relevant to both bed design and in vehicle seat design.

NEDERLANDSE SAMENVATTING

Het interieur van voertuigen zal veranderen als gevolg van technische ontwikkelingen, aandacht voor het milieu en (gerelateerd) veranderend gebruikersgedrag. Verminderen van het gewicht van het interieur van voertuigen is wenselijk om het energieverbruik te beperken, maar tegelijkertijd moeten geen concessies gedaan worden aan het comfort. Globalisering en nieuwe trends zoals geautomatiseerd rijden, nieuwe voorstuwingstechnieken in de luchtvaart en het promoten van (langeafstands- en slaap-) treinen vragen om nieuwe interieurontwerpen. Deze nieuwe interieurs moeten stimuleren om productief te zijn tijdens het transport, te ontspannen en te slapen.

Dit proefschrift heeft tot doel ontwerprichtlijnen of suggesties te bieden voor ontwerpers en ingenieurs om hen te helpen bij het ontwerpen van comfortabele en nuttige zit- en slaapomgevingen in voertuigen (o.a. treinen, vliegtuigen, (geautomatiseerde) auto's, schepen en onderzeeërs).

Bij comfortonderzoek moet rekening worden gehouden met menselijke activiteiten en het effect van tijd (Deel 1). Bij comfortonderzoek is het van belang om aan te geven wat deelnemers deden voordat ze aan de test deelnamen (eerdere activiteiten), hoe ze bewegen/zich gedragen tijdens de test, welke houdingen ze aannemen, of er stimuli worden gebruikt die het gedrag afleiden of beïnvloeden en of deelnemers zich bewust zijn van de tijd of het einde/duur van activiteiten/stimuli (Hoofdstuk 2). Er wordt ook getoond hoe de tijd de comfortervaring beïnvloedt, waarbij het ongemak zich naar het einde toe stabiliseert of afneemt en het comfort stabiliseert of toeneemt. Het feit dat deelnemers zich bewust zijn van de tijd kan van invloed zijn op de beoordeling van comfort (Hoofdstuk 3).

Eén manier om comfortabele, lichtgewicht stoelen te ontwerpen, is door ze te baseren op de menselijke contouren (Deel 2). De menselijke contour kan worden bepaald met behulp van 3D scans, zodat materiaal kan worden weggelaten waar het niet nodig is. Een stoel gebaseerd op menselijke contouren heeft het voordeel dat het ook comfortabel is vergeleken met een traditionele stoel (Hoofdstuk 4). Het maakt een vermindering van het stoelgewicht en het stoelvolumen mogelijk. Dat is in dit proefschrift aangetoond bij een business class, premium economy en economy class vliegtuigstoel (Hoofdstuk 5). Door de optimalisatie van de drukverdeling, kon met gebruik van nieuwe materialen in de zitting (bijvoorbeeld een vering van schuim of geweven gaas) en topologie-geoptimaliseerde structuren het gewicht verminderd worden en tegelijkertijd het comfort worden verbeterd (Hoofdstuk 4 en 6). Het behalen van een vergelijkbare of gunstigere comfortscore en een lager gewicht is gunstig voor het verminderen van de impact op het milieu, wat relevant is voor het toekomstige interieur van voertuigen (zoals besproken in de inleiding).

De activiteit die de meeste langeafstandspassagiers het belangrijkst vinden, maar vaak ook als moeilijk ervaren, is slapen (Deel 3). Deel 3 onderzoekt hoe men slaapt in een liggende houding. Waar gezonde mensen zich normaal tijdens de slaap vrij moeten kunnen bewegen, beïnvloedt het beperken van de ruimte in voertuigen de slaapkwaliteit, efficiëntie en comfort. Op de zij en rug liggen zijn de dominante slaaphoudingen, maar er vindt ook veel variatie in houding plaats tijdens natuurlijk slaapgedrag. Bij het slapen in bed of stoel is het

belangrijk dat het ontwerp die variatie in houding mogelijk maakt, evenals de microbewegingen die nodig zijn om natuurlijk slaapgedrag te faciliteren (Hoofdstuk 7). De slaapruijnte kan worden verkleind, maar dit heeft een negatieve invloed op de slaapkwaliteit en het comfort. Dit proefschrift laat zien dat bij een ruimtereductie van ~25% de slaapkwaliteit, efficiëntie en comfort redelijk acceptabel lijken (Hoofdstuk 8). Het is echter aan ontwerpers en ingenieurs om de slaapruijnte en de slaapkwaliteit, de slaapefficiëntie en het comfort bewust af te wegen tegen andere vereisten, zoals economische eisen (denk aan ruimte en gewicht, en diens impact op brandstof verbruik) en operationele veiligheid.

Een andere veel voorkomende ontspannende activiteit is het kijken naar in-voertuig-amusement op een scherm, en dutten/slapen in een achteroverleunende stoel (Deel 4). Omdat mensen de voorkeur geven aan een onderuitgezakte houding bij het kijken naar een scherm, ontbreekt het hen vaak aan voldoende ondersteuning voor hoofd en nek. Dergelijke ondersteuning door middel van een hoofdsteen is comfortabeler, maar verlaagt de spieractiviteit niet (op basis van EMG data). Een mogelijke verklaring hiervoor is dat mensen de neiging hebben om een neutrale houding met minimale spieractiviteit te zoeken (Hoofdstuk 9). Om ontwerpers, ingenieurs en wetenschappers te helpen bij het ontwerpen van hoofdsteenen voor het kijken naar een scherm en achteroverleunend slapen, werd een hoofdgevoeligheidsmodel ontwikkeld (welke ook gebruikt kan worden in andere industrieën en toepassingen, zoals gelaatsmaskers, brillen en hoofdtelefoons). Dit model laat zien dat hoge druk moet worden vermeden rond het oor, de slaap en de nek, waar het grootste deel van de belasting van het hoofd kan worden gedragen door een hoofdsteen op de achterkant van het hoofd en de kaaklijn (Hoofdstuk 10).

De centrale onderzoeksvraag van dit proefschrift was: *Wat zijn de fysieke ergonomische factoren die het zitcomfort, het ontspanningscomfort en de slaapkwaliteit en -comfort beïnvloeden?* Uit de onderzoeken beschreven in dit proefschrift blijkt dat fysieke factoren invloed hebben op het zit-, ontspannings- en slaapcomfort en de slaapkwaliteit. In het algemeen laten de cases uit dit proefschrift zien dat het rekening houden met de menselijke contouren, de menselijke gevoeligheid, menselijk gedrag en de invloed van tijd kan leiden tot comfortabelere, effectievere en potentieel veiligere zit- en slaapomgevingen in voertuigen. Bestaande literatuur, zoals besproken in de hoofdstukken, ondersteunt deze conclusies. In veel gevallen is verder onderzoek nodig om te komen tot meer onderbouwde en gedetailleerde richtlijnen voor industrie en wetenschap. Dit geldt vooral voor het ontwerpen voor slapen onderweg.

Zoals blijkt uit dit proefschrift moet het ontwerp van stoelen gebaseerd zijn op activiteiten, om rekening te houden met natuurlijk gedrag, houdingsvariatie en bewegingen in de stoel, aangezien deze het comfort van de gebruiker beïnvloeden. Zitplaatsen met menselijke contouren kunnen het zitcomfort verbeteren en het gewicht verminderen. Hoewel slaapergonomie enige aandacht krijgt in de wetenschap, is het verrassend hoe beperkt het wetenschappelijke veld op het gebied van slaapergonomie is ontwikkeld. Hoewel er in dit proefschrift een eerste stap is gezet, zou er meer aandacht moeten worden besteed aan de slaapergonomie, aangezien dit relevant is voor zowel het ontwerpen van bedden als voor het ontwerpen van voertuigstoelen.

Chapter 1

GENERAL INTRODUCTION

DESIGN FOR COMFORTABLE TRAVEL

1.1. Background on interior design for transit

1.1.1. Push for change

The way people travel is changing due to globalisation, population growth (United Nations Department of Economic Social Affairs - Population Division, 2022), urbanisation (OECD/European Commission, 2020), climate change (IPCC, 2022) and technological developments. *“New technologies such as automated driving and electrification, but also long-term trends such as urbanisation and/or changing consumer behaviour make mobility a global concern”* (PWC, 2023). The Dutch government also states that it *“is committed to providing a traffic and transport system that will help citizens travel quickly, safely and comfortably. One of the challenges it faces is how to do this sustainably”* (Rijkswaterstaat, 2023). The European Union intends to boost long-distance and cross-border passenger rail services for economic and sustainability reasons (Committee on Transport and Tourism, 2022; European Commission; Directorate-General for Mobility and Transport, 2020). The EU is also making new policies, pushing for implementing ERTMS (European Rail Traffic Management System), and investing in rail infrastructure and new rollingstock, with the aim of doubling EU (cross-border) high-speed rail by 2030 (Committee on Transport and Tourism, 2022; Directorate-General for Mobility and Transport, 2021). These new technologies, environmental concerns, changing policies, investments and changing human behaviours pose challenges and opportunities for mobility design, both on a macro (e.g. infrastructure, networks, governmental policies and investments) and on a micro (e.g. vehicle development and interior design) level.

Vehicle interior design is a vital part in mobility, as it is closely associated with safety and comfort of passengers (Fuchs & Brandstätter, 2021) and primary its weight impacts the sustainability of the transportation modes. For instance, a large aircraft has 6 tonnes of interior parts (SMTC, 2014) and 19% of a car's (2009 Toyota Venza) weight concerns the interior (Lotus Engineering Inc., 2010). Also due to electrification and automation of cars, car manufacturers emphasise the differentiation needed in the car interior (Rössger, 2023). For instance, in L3, L4 and L5 automated driving (SAE International, 2021) (a.k.a. autonomous or self-driving¹), it is possible for the ‘driver’ to perform other activities than driving (Lutin, 2018). Sustainability concerns have revamped the interest in long-distance, high-speed and sleeper trains (Committee on Transport and Tourism, 2022; European Commission - Directorate-General for Mobility and Transport, 2020; European Environment Agency, 2021; Rapid Transition Alliance, 2022) and make governments increase investments in rapid public transit (i.e. trains, trams, light-rail, metro, and bus rapid transit (BRT)) (KPMG, 2022; Ministry of Infrastructure and Water Management et al., 2019). Some examples of rapid public transit projects are HS2 by the Department for Transport (2020) in the UK, Grand Paris Express by Societe du Grand Paris (2023) in France, Suburban Rail Loop by the State Government of Victoria (2023) in Melbourne Australia, and Line 1 Ho Chi Minh City Metro by the Management Authority for Urban Railways (2023) in Vietnam. Economic and sustainability concerns also push the aviation industry towards exploring more efficient aircraft (Afonso et al., 2023) and cabin concepts such as the flying-V (Vink, Rotte, Anjani, Percuoco, & Vos, 2020) and improving on more efficient (but currently slower, more vibrating and noisier) aircraft with propeller

propulsion (Vink, Vledder, Monteiro, & Song, 2022). Lastly, also the nautical sector changes, for instance with more sustainable and efficient propulsion and reduction of drag (Tadros, Ventura, & Soares, 2023). Especially the harsh environments and optimisation of the use of space provoke challenges to the interior, in particular in sleeping environments on nautical vessels (i.e. ships, submarines, offshore rigs) (Hansen & Holmen, 2011; Matsangas & Shattuck, 2021; Stevens & Parsons, 2002). This is particularly relevant for navy vessels, which need to be compact for security (small radar/sonar cross-section), operational (reach remote locations) and endurance/economic reasons (fuel consumption).

All these new and improved vehicles require new interiors including seat designs tailored to the specific needs and requirements of the stakeholders, and in particular the seat occupant. This is especially true for vehicles in which passengers (both leisure and business) and professionals spend a prolonged time, where comfort becomes an important factor in passenger experience, and employee effectiveness and operational safety.

¹ Automated, self-driving, autonomous and driverless vehicles have different meanings and interpretations, and are often interchangeably used (Park, Khattak, & Smith, 2018). This dissertation uses the SAE/ISO standard definition for automated vehicles (SAE International, 2021).

1.1.2. Human activities in transit

As humans we are more mobile than ever before; this also changes our behaviour. Technology allows us now to work, entertain and connect everywhere with laptops, mobile phones, tablets and telecommunication (internet). Travel is no longer *spending time in transit*, but can – and thereby sometimes needs to – be spending time on productivity, relaxing and rest (Frei, Mahmassani, & Frei, 2015; Wilson, Gyi, Morris, Bateman, & Tanaka, 2022). Working during travel in current vehicles was observed, however, less popular (Malichová, Cornet, & Hudák, 2022) due to space restrictions, vehicle vibration, motion sickness, environmental nuances, and lack of sufficient connectivity. In a 2014 study in Germany, respondents did not seem to see themselves spending time working in autonomous vehicles in the future, and perceived such vehicle benefits to spend time on window gazing, talking to companions, and relaxing (Fraedrich, Cyganski, Wolf, & Lenz, 2016).

This makes relaxing, resting and recovering a sensible way of spending travel time. For some, it is one of the few opportunities for *'time out'* (time to be oneself and/or spend on a specific personal leisure activity, e.g. reading, listening to music) or travel functions as a *'transition time'* (creating mental distance between start and destination, and/or preparing for the destination's demands) (Jain & Lyons, 2008). By sleeping and relaxing during travel, one is less aware of the restrictions of travel, and one spends time effectively in order to be productive at the destination. This is one of the main reasons why business class travellers are willing to pay a premium for the privilege of proper sleep facilities like a full-flat bed; to be rested (and slightly more adjusted to the new time zone) when landed, and thus be productive straight away after landing (Smulders, 2018). Also, passengers participating in active leisure activities (which result in a higher quality of

experience and contribute to individual well-being) (Frei et al., 2015) and who are able to spend their travel time usefully (Kouwenhoven & de Jong, 2018) tend to have a more positive attitude toward the value of transit.

In designing a vehicle seat, it is important to consider the human behaviour (Smulders and Vink (2021), see Chapter 2), activities performed and their corresponding postures (Groenesteijn et al. (2014); Hiemstra-van Mastrigt, Groenesteijn, Vink, and Kuijt-Evers (2017); Hiemstra-van Mastrigt, Meyenborg, and Hoogenhout (2016); Kamp, Kilincsoy, and Vink (2011); Liu, Yu, and Chu (2019); Smulders et al. (2016), see Chapter 4) by users in those seats and spaces (context), to facilitate comfortable travel. Activity based seat design can help to spend time in transit effectively, increasing the willingness to take such modes of transport and increase user satisfaction (Frei et al., 2015).

1.2. The challenge of designing for long-distance travel: balancing seating and sleeping comfort against economics and operational safety

In transit, a passenger spends almost the entire duration of travel in their seat. The seat, vehicle environment and social context create a limited space envelope for the occupant, which limits their postures, movement and thereby activities. The passenger's desire for adequate living space stands in opposition to vehicle economics, as vehicle volume and weight affect energy use for vehicle locomotion and come with the associated financial and environmental costs. To compensate for the limited amount of living space in the cabin, vehicle seats may offer adjustability to facilitate multiple activities and their associated postures, such as backrest recline and leg support, headrest adjustability and an adjustable table.

To make things even more challenging, vehicle seats have to meet strict safety requirements, e.g. materials must meet flammability regulations and the construction needs to withstand stresses of a crash. Seats should also offer a comfortable travel experience for prolonged durations for passengers with different anthropometry, such as length (tall vs small) and body size (obese vs slim). And lastly, in the context of public transport (e.g. aircraft, train and bus), the seat has to endure prolonged and intensive (ab)use and vandalism by passengers for about ten years (Eisenbrand, 2004; Garcia & Skift, 2014; Le, 2015; Schultheis, 2016; Snider, 2016).

The conflict of interest between the comfort requirements of passengers, the economical driven spatial constraints, weight and durability requirements of operators (e.g. airlines, railways, bus companies), safety standards and governmental safety and sustainability regulations are a fundamental condition of seat design and production. This makes seat design and manufacturing a complex and challenging feat.

1.2.1. The (dis)comfort of long-distance travel

Many studies show that discomfort increases in aircraft seats (Smulders et al., 2016; Vink, Anjani, Smulders, & Hiemstra-van Mastrigt, 2017) and car seats (Sammonds, Fray, & Mansfield, 2017) over time. Among observed activities conducted in the airplane, the discomfort is rated highest during sleeping (Bouwens, Tsay, & Vink, 2017), possibly as many airplane seats insufficiently facilitate sleep. To reduce discomfort, a possible solution is variation in activities. This could be walking through the airplane (Hiemstra-van Mastrigt et al., 2016), having a 15 minute walking break to break-up a car trip of 2 hours (Sammonds, Mansfield, & Fray, 2017), or movements within the seat (Bouwens et al., 2018). This asks for a seat that allows for a variation in activities and supports a variation of related postures.

1.2.2. Entertainment in transit

One way to distract passengers from discomfort is watching IVE (In-Vehicle Entertainment), in aviation known as IFE (In-Flight Entertainment). Lewis et al. (2016) showed that passengers can be distracted from discomfort by gaming and watching IFE. Also Bouwens et al. (2018) showed that playing a game increases comfort significantly in an aircraft seat. Hiemstra-van Mastrigt, Kamp, Van Veen, Vink, and Bosch (2015) showed a positive effect of exercising by means of a game in a car seat on comfort. However, the ideal position of IVE in relation to the preferred passenger posture is unknown, as current guidelines and recommendations for watching a screen predominantly focus on VDU (visual display unit) work.

1.2.3. Sleeping in transit

For sleeping, a lot is unknown about sleep ergonomics, such as physical dimensions. Sleep facilities in vehicles (such as aircraft, trains, busses, ships, submarines, and (automated) cars) often have a limited space due to vehicle design, economic and/or operational reasons (Smulders, 2018; Stanglmeier et al., 2020). Providing effective and comfortable sleep in vehicles is important for:

1. ... passenger satisfaction (Kluge, Ringbeck, & Spinler, 2020), product differentiation and to justify surplus prices (Hugon-Duprat & O'Connell, 2015; Kuo & Jou, 2017). After ticket price and flight schedule, onboard comfort is the most important decision factor for buying a ticket in aviation (IATA Economics, 2016). Also, passengers spend most time during flight, and rate as most important activities, sleeping (~35% time spent, most important) and watching IFE (~34% time spent, 2nd most important) (Smulders, 2018).
2. ... crew effectiveness and operational safety in safety critical environments, such as those of aircraft cabin crews (Avers, King, Nesthus, Thomas, & Banks, 2009; Drury, Ferguson, & Thomas, 2012; Hartzler, 2014), medical staff (Dorrian et al., 2008; Gold et al., 1992; Weinger & Ancoli-Israel, 2002), offshore and maritime workers (Hope, Øverland, Brun, & Matthiesen, 2010; Hystad, Nielsen, & Eid, 2017; Sneddon, Mearns, & Flin, 2013) and military personnel (Good, Brager, Capaldi, & Mysliwiec, 2020; Grandou, Wallace, Fullagar, Duffield, & Burley, 2019; Parker & Parker, 2017).

Sleeping in transit can take place in two different configurations: *reclined sleeping* in a seat and *full-flat sleeping* in a (bunk)bed. The choice for each configuration will have consequences for sleep quality and comfort. In particular the seat recline and support, and the bed space envelope will impact sleep ergonomics. There are minimal standards for sleep facilities in safety critical environments such as aircraft (Federal Aviation Administration, 2012; Simons & Spencer, 2007), but no guidelines exist on minimal sleep space envelopes in relation to sleep quality and comfort. Such guidelines could help designers and engineers to design qualitative, effective, comfortable and compact seating and sleep facilities. Guidelines could also help in making a conscious decision on balancing the economics of space volume and weight (costs) against passenger comfort and their willingness to pay for that comfort.

1.2.4. Scientific gap

Not all vehicle interiors are fully adapted to these (new) trends and related human behaviours due to space restrictions and regulations. Background information is missing for designers and engineers to make informed considerations in balancing volume and weight (which influences energy consumption) vs occupant comfort and sleep effectiveness. There is a need for background information between understanding of the physical factors and comfort over time in general, as well as in the context of seating, relaxing and sleeping. In the struggle between accommodating human activities and the limited space provided by the vehicles, designers and engineers might ask for a guideline regarding volume and weight versus occupant comfort and sleep effectiveness for an optimum, if not possible, a balanced solution.

1.3. Aim of this dissertation

The aim of this dissertation is to provide ergonomic background information and suggestions for designers and engineers to aid them in designing comfortable and useful seating and sleeping environments in vehicles (e.g. trains, aircraft, (automated) cars, ships, and submarines). Such background information and recommendations could aid designers and engineers to make a conscious decision on balancing vehicle economics of space volume and weight (costs) against passenger comfort and their (or their employer's) willingness (or obligation) to pay for that comfort, operational effectiveness, and safety. Some studies in this dissertation are predominantly within the aviation context, but the dissertation as a whole aims to be applicable in a broader context; i.e. not solely applicable to one type of vehicle (e.g. aircraft, train, car, or nautical vessel) nor on one type of passengers (e.g. leisure-, business-, commute- travellers or vehicle crew), so that resulting knowledge can be applied in multiple vehicles and contexts.

1.3.1. Research questions

To provide ergonomic background information and suggestions for designers and engineers to aid them in designing comfortable and useful seating and sleeping environments in vehicles, the overarching research question (RQ) of this dissertation is: *What are physical ergonomic factors that influence seating comfort, relaxing comfort and sleeping quality and comfort?* Based on this overarching RQ, four main RQs, each having a subset of RQs, are proposed in this dissertation. The main RQs and their subset RQs are listed as:

- 1. How does human behaviour and time impact comfort?**
 - 1.1. Should human behaviour be recorded in (dis)comfort research?
 - 1.2. How does (dis)comfort change over time?
 - 1.3. In a situation where comfort is low and/or discomfort is high, will the discomfort reduce and/or the comfort increase near the end of an experiment?
- 2. How to design a seat based on the human contour?**
 - 2.1. How to design a light weight seat pan and backrest based on the human contour using 3D scan technology?
 - 2.2. How does a light weight human contour shaped aircraft seat affect comfort, discomfort and pressure distribution compared to a traditional aircraft seat?
 - 2.3. How to design a light weight seat pan and backrest based on the human body contour using 3D scan methods?
 - 2.4. Can a foam spring technology in an aircraft seat pan reduce weight and at the same time provide equal or better comfort?
- 3. How to improve sleep quality in full-flat sleeping in transit within minimal space?**
 - 3.1. What are common postures in full-flat sleeping?
 - 3.2. What effect does a minimal space envelope have on sleep quality, sleep efficiency and comfort?
- 4. How to improve reclined watching IVE in transit by means of a headrest?**
 - 4.1. Does head support provide comfort and lower muscle activity for watching IFE in a reclined seat position?
 - 4.2. What is the head, face and neck pressure discomfort threshold of the human skin?

1.4. Dissertation outline

This dissertation is divided into four parts, each answering one of the research questions respectively, that together aim to contribute to answering the overarching research question. Each part consists of multiple chapters that are based on publications and that predominantly follow the structure of introduction, method, results, discussion and conclusion. The dissertation concludes with a general discussion and conclusion, which gives research and design recommendations. Unexplored but related topics are presented here as well. Table 1.1 shows the structure of this dissertation and the following paragraphs describe the highlights of each section. Figure 1.1 gives an overview of how the chapters in this dissertation relate to the human and seat.

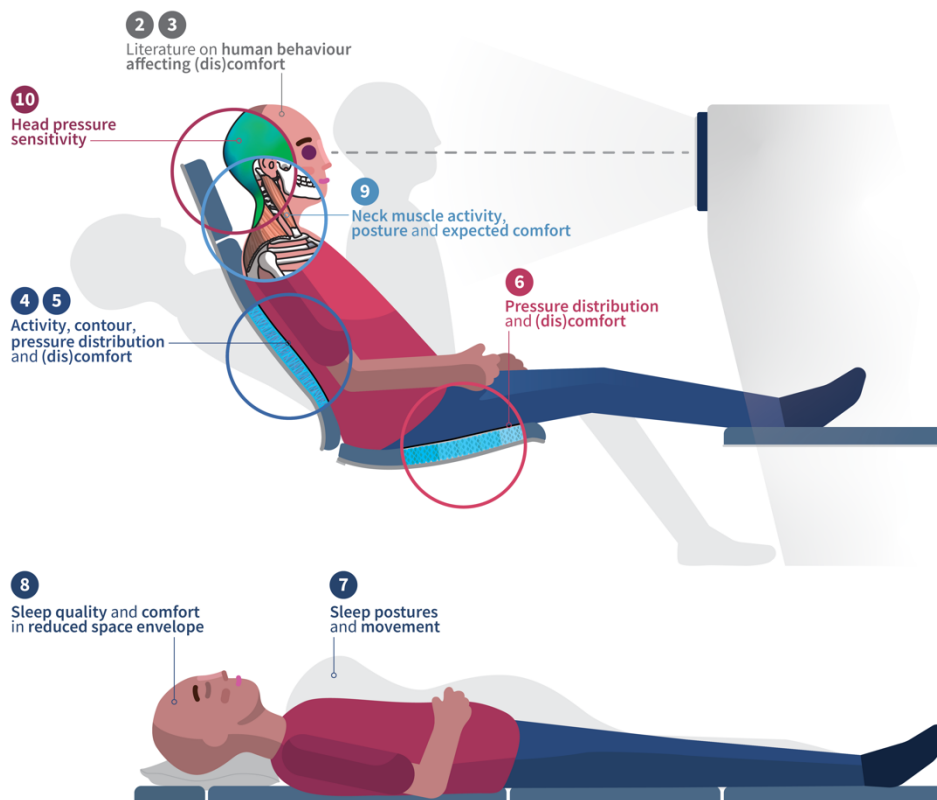


Figure 1.1 | Overview of the chapters in this dissertation and their relation to the human and seat.

1.4.1. Part 1: (Dis)comfort and human behaviour

Part 1 focusses on answering research question 1: *How does human behaviour and time impact comfort?*

Human behaviour is important to consider in comfort research and seat design. The user activities determine what postures (and posture transitions) and support should be facilitated to perform such activities. Also *managing* one's comfort experience over time can help to improve the all-over experienced comfort.

Part 1 emphasises the importance of taking into account human behaviour and comfort experience over time in seat design.

1.4.2. Part 2: Design for seating in transit based on the human contour

Part 2 focusses on answering research question 2: *How to design a seat based on the human contour?*

Designing human contour-based seating can improve comfort, and can also offer opportunities in reducing weight as double curved structures are stronger and stiffer than single curved structures. However, these curved seats should still allow for different activities (which are often context dependent) and their related postures, and should fit a wide variety of population anthropometrics.

Part 2 discusses multiple projects on designing activity-, context- and human contour-based seating, shows opportunities for seat design and gives recommendations on the design process.

1.4.3. Part 3: Design for full-flat sleep in transit

Part 3 focusses on answering research question 3: *How to improve sleep quality in full-flat sleeping in transit within minimal space?*

Sleeping is one of the most performed activities and rated as one of the most important/ preferred activities on long-distance travel. It is also one of the dominant factors in class differentiation and tier pricing; some passengers are willing to pay more for the benefit of adequate sleep. Working during travel is a productive way of spending time, but can be difficult due to the environment (space restrictions and noise) and connectivity limitations. This makes rest and recovery a very sensible alternative of spending travel time effectively. By sleeping during travel, we are less aware of the restrictions and discomfort that travel gives us and we spend the time effectively (one needs to sleep anyway) to be productive at our destination. Also in a professional context, especially in safety critical environments (such as aviation, offshore, military, and medical contexts), sleep quality and comfort have a major impact on crew effectiveness and thereby safety. However, vehicle interiors are not always fully adapted to this human behaviour and need.

Part 3 contains a literature review of sleeping postures, followed by an experiment on how the space envelope influences sleep quality, effectiveness and comfort. Based on this, designers and engineers can balance the required sleep quality, effectiveness and comfort against space volume for the intended context.

1.4.4. Part 4: Design for entertainment and reclined sleeping in transit

Part 4 focusses on answering research question 4: *How to improve reclined watching IVE in transit by means of a headrest?*

Watching entertainment is another predominantly performed activity and is rated as one of the most important/preferred activities on long-distance travel. A possible explanation for this is that it distracts from the restrictions and discomfort of travel. As entertainment consumption is more of a passive activity, people tend to take a more slouched posture. This affects the support needed, and especially a headrest can play an important role here in comfort.

Also, sleep is a dominant and highly requested activity in transit. As space in vehicles can be scarce, designers can consider facilitating reclined sleeping. As reclined sleep provides less sleep quality and comfort opposed full-flat sleep, providing adequate head support could help here.

Part 4 discusses how headrest design can impact seating comfort. Although the focus is given on vehicle entertainment, insights are also relevant for headrest design that supports the head in a reclined sleeping context (where space is scarce and full-flat sleeping is not possible).

1.4.5. Chapter 11: General discussion and conclusion

Chapter 11 reflects on the studies presented in this dissertation. It gives an overview of the study results and answers the research questions. Based on the studies presented, recommendations for further research and for industry are formulated.

Table 1.1 | Structure of this dissertation.

Part	Part title	Ch.	Publications / Chapter title	Journal ¹ / Congress ² / Book chapter ³
		1	General introduction: design for comfortable travel	—
1	(Dis)comfort and human behaviour	2	Smulders, M. and Vink, P. (2021). Human behaviour should be recorded in (dis) comfort research. <i>Work</i> , 68(s1), S289-S294.	Work ¹
		3	Vink, P., Anjani, S., Smulders, M. and Hiemstra-van Mastrigt, S. (2017). Comfort and discomfort effects over time: the sweetness of discomfort and the pleasure towards of the end. <i>1st International Comfort Congress</i> , Salerno, Italy.	ICC 2017 ²
2	Design for seating in transit based on the human contour	4	Smulders, M., Berghman, K., Koenraads, M., Kane, J. A., Krishna, K., Carter, T. K. and Schultheis, U. (2016). Comfort and pressure distribution in a human contour shaped aircraft seat (developed with 3D scans of the human body). <i>Work</i> , 54(4), 925-940.	Work ¹
		5	Hiemstra-van Mastrigt*, S., Smulders*, M., Bouwens, J. M. and Vink, P. (2019). Designing aircraft seats to fit the human body contour. In <i>DHM and Posturography</i> (pp. 781-789). Academic Press.	DHM and Posturography ³
		6	Dangal, S., Smulders, M. and Vink, P. (2021). Implementing spring-foam technology to design a light weight and comfortable aircraft seat-pan. <i>Applied Ergonomics</i> , 91, 103174.	Applied Ergonomics ¹
3	Design for full-flat sleep in transit	7	Smulders, M., Song, Y. and Vink, P. (2021) Sleeping postures and movement in adults: a literature review. <i>3rd International Comfort Congress</i> , Nottingham, UK.	ICC 2021 ²
		8	Smulders, M., Song, Y., and Vink, P. (2021) Sleep quality and (dis)comfort in a minimal space envelope. <i>The 21st Triennial Congress of the International Ergonomics Association</i> , Vancouvers, Canada.	IEA 2021 ²
4	Design for entertainment and reclined sleep in transit	9	Smulders, M., Naddeo, A., Cappetti, N., Van Grondelle, E. D., Schultheis, U. and Vink, P. (2019). Neck posture and muscle activity in a reclined business class aircraft seat watching IFE with and without head support. <i>Applied ergonomics</i> , 79, 25-37.	Applied Ergonomics ¹
		10	Smulders, M., van Dijk, L. N. M., Song, Y., Vink, P. and Huysmans, T. (2023). Dense 3D pressure discomfort threshold (PDT) map of the human head, face and neck: A new method for mapping human sensitivity. <i>Applied Ergonomics</i> , 107, 103919.	Applied Ergonomics ¹
		11	General discussion and conclusions: recommendations for research and design	—

* Shared first author

¹ Journal publication² Congress publication³ Book chapter

1.5. References

- Afonso, F., Sohst, M., Diogo, C.M., Rodrigues, S.S., Ferreira, A., Ribeiro, I., . . . Portugal-Pereira, J. (2023). Strategies towards a more sustainable aviation: A systematic review. *Progress in Aerospace Sciences*, 137, 100878.
- Avers, K.B., King, S.J., Nesthus, T.E., Thomas, S., & Banks, J. (2009). *Flight Attendant Fatigue, Part 1: National Duty, Rest, and Fatigue Survey*. (DOT/FAA/AM-09/24). Oklahoma City: Civil Aerospace Medical Institute, Federal Aviation Administration. Retrieved from <https://apps.dtic.mil/sti/pdfs/ADA520848.pdf>.
- Bouwens, J.M.A., Fasulo, L., Hiemstra-van Mastrikt, S., Schultheis, U.W., Naddeo, A., & Vink, P. (2018). Effect of in-seat exercising on comfort perception of airplane passengers. *Applied ergonomics*, 73, 7-12. doi:10.1016/j.apergo.2018.05.011
- Bouwens, J.M.A., Tsay, W.-J.J., & Vink, P. (2017). The high and low comfort peaks in passengers' flight. *WORK*, 58(4), 579-584. doi:10.3233/WOR-172637
- Committee on Transport and Tourism. (2022). *Report on the action plan to boost long-distance and cross-border passenger rail*. (A9-0242/2022). European Parliament
- Department for Transport. (2020). *Full Business Case High Speed 2 Phase One*. London, United Kingdom. Retrieved from <https://www.gov.uk/government/publications/hs2-phase-one-full-business-case>.
- Directorate-General for Mobility and Transport. (2021). *Action plan to boost long distance and cross-border passenger rail*. (52021DC0810). Strasbourg: European Commission. Retrieved from <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2021:810:FIN>.
- Dorrian, J., Tolley, C., Lamond, N., van den Heuvel, C., Pincombe, J., Rogers, A.E., & Drew, D. (2008). Sleep and errors in a group of Australian hospital nurses at work and during the commute. *Applied ergonomics*, 39(5), 605-613. doi:10.1016/j.apergo.2008.01.012
- Drury, D.A., Ferguson, S.A., & Thomas, M.J. (2012). Restricted sleep and negative affective states in commercial pilots during short haul operations. *Accident Analysis & Prevention*, 45, 80-84. doi:10.1016/j.aap.2011.09.031
- Eisenbrand, J. (2004). "More legroom please": A historical survey of the aircraft seat. In *Airworld: Design and Architecture for Air Travel* (pp. 124-142). Germany: Vitra Design Museum.
- European Commission - Directorate-General for Mobility and Transport. (2020). *Sustainable and Smart Mobility Strategy – putting European transport on track for the future*. (52020DC0789). Brussels
- European Environment Agency. (2021). *Transport and environment report 2020 - Train or plane?* (Report no. 19/2020). Luxembourg: Publications Office of the European Union. Retrieved from https://www.eea.europa.eu/ds_resolveuid/D6WTPN8CIS. doi:10.2800/43379
- Federal Aviation Administration. (2012). *Flightcrew Member Rest Facilities* (AC 117-1). Federal Aviation Administration Retrieved from https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/1020336.

- Fraedrich, E., Cyganski, R., Wolf, I., & Lenz, B. (2016). User perspectives on autonomous driving: a use-case-driven study in Germany.
- Frei, C., Mahmassani, H.S., & Frei, A. (2015). Making time count: Traveler activity engagement on urban transit. *Transportation Research Part A: Policy and Practice*, 76, 58-70.
- Fuchs, A., & Brandstätter, B. (2021). *Future Interior Concepts* (1st ed.). Cham, Switzerland: Springer Nature Switzerland AG. doi:doi.org/10.1007/978-3-030-51044-2
- Garcia, M., & Skift. (2014). *The Future of the Aircraft Cabin: Tracking Trends and Debunking Myths*. Retrieved from skift.com/wp-content/uploads/2014/09/23-SkiftReport-The-Future-of-the-Aircraft-Cabin.pdf
- Gold, D.R., Rogacz, S., Bock, N., Tosteson, T.D., Baum, T.M., Speizer, F.E., & Czeisler, C.A. (1992). Rotating shift work, sleep, and accidents related to sleepiness in hospital nurses. *American journal of public health*, 82(7), 1011-1014. doi:10.2105/ajph.82.7.1011
- Good, C.H., Brager, A.J., Capaldi, V.F., & Mysliwiec, V. (2020). Sleep in the United States military. *Neuropsychopharmacology*, 45(1), 176-191. doi:10.1038/s41386-019-0431-7
- Grandou, C., Wallace, L., Fullagar, H.H., Duffield, R., & Burley, S. (2019). The effects of sleep loss on military physical performance. *Sports Medicine*, 49(8), 1159-1172. doi:10.1007/s40279-019-01123-8
- Groenesteijn, L., Hiemstra-van Mastrigt, S., Gallais, C., Blok, M., Kuijt-Evers, L., & Vink, P. (2014). Activities, postures and comfort perception of train passengers as input for train seat design. *Ergonomics*, 57(8), 1154-1165.
- Hansen, J.H., & Holmen, I.M. (2011). Sleep disturbances among offshore fleet workers. A questionnaire-based survey. *International maritime health*, 62(2), 123-130.
- Hartzler, B.M. (2014). Fatigue on the flight deck: the consequences of sleep loss and the benefits of napping. *Accident Analysis & Prevention*, 62, 309-318. doi:10.1016/j.aap.2013.10.010
- Hiemstra-van Mastrigt, S., Groenesteijn, L., Vink, P., & Kuijt-Evers, L.F. (2017). Predicting passenger seat comfort and discomfort on the basis of human, context and seat characteristics: a literature review. *Ergonomics*, 60(7), 889-911.
- Hiemstra-van Mastrigt, S., Kamp, I., Van Veen, S., Vink, P., & Bosch, T. (2015). The influence of active seating on car passengers' perceived comfort and activity levels. *Applied ergonomics*, 47, 211-219.
- Hiemstra-van Mastrigt, S., Meyenborg, I., & Hoogenhout, M. (2016). The influence of activities and duration on comfort and discomfort development in time of aircraft passengers. *WORK*, 54(4), 955-961.
- Hope, S., Øverland, S., Brun, W., & Matthiesen, S.B. (2010). Associations between sleep, risk and safety climate: A study of offshore personnel on the Norwegian continental shelf. *Safety Science*, 48(4), 469-477. doi:10.1016/j.ssci.2009.12.006
- Hugon-Duprat, C., & O'Connell, J.F. (2015). The rationale for implementing a premium economy class in the long haul markets—Evidence from the transatlantic market. *Journal of Air Transport Management*, 47, 11-19. doi:10.1016/j.jairtraman.2015.03.005

- Hystad, S., Nielsen, M., & Eid, J. (2017). The impact of sleep quality, fatigue and safety climate on the perceptions of accident risk among seafarers. *European review of applied psychology*, 67(5), 259-267. doi:10.1016/j.erap.2017.08.003
- IPCC. (2022). Mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA doi:10.1017/9781009157926.001
- Jain, J., & Lyons, G. (2008). The gift of travel time. *Journal of transport geography*, 16(2), 81-89.
- Kamp, I., Kilincsoy, Ü., & Vink, P. (2011). Chosen postures during specific sitting activities. *Ergonomics*, 54(11), 1029-1042.
- Kluge, U., Ringbeck, J., & Spinler, S. (2020). Door-to-door travel in 2035–A Delphi study. *Technological Forecasting and Social Change*, 157, 120096. doi:10.1016/j.techfore.2020.120096
- Kouwenhoven, M., & de Jong, G. (2018). Value of travel time as a function of comfort. *Journal of Choice Modelling*, 28, 97-107.
- KPMG. (2022). *Future of public transport*. Retrieved from <https://assets.kpmg.com/content/dam/kpmg/xx/pdf/2022/11/future-of-public-transport-report.pdf>
- Kuo, C.-W., & Jou, R.-C. (2017). Willingness to pay for airlines' premium economy class: The perspective of passengers. *Journal of Air Transport Management*, 59, 134-142. doi:10.1016/j.jairtraman.2016.12.005
- Le, N.T.P. (2015). *Thesis: The design of a next generation Y class aircraft seat*. Retrieved from resolver.tudelft.nl/uuid:f4307eb4-f448-40d9-b65a-5a0a3356904f
- Lewis, L., Patel, H., Cobb, S., D'cruz, M., Bues, M., Stefani, O., & Grobler, T. (2016). Distracting people from sources of discomfort in a simulated aircraft environment. *WORK*, 54(4), 963-979. doi:10.3233/WOR-162356
- Liu, J., Yu, S., & Chu, J. (2019). The passengers' comfort improvement by sitting activity and posture analysis in civil aircraft cabin. *Mathematical Problems in Engineering*, 2019, 1-10. doi:10.1155/2019/3278215
- Lotus Engineering Inc. (2010). An assessment of mass reduction opportunities for a 2017–2020 model year vehicle program. *Lotus Engineering Inc.*
- Lutin, J.M. (2018). Not if, but when: Autonomous driving and the future of transit. *Journal of Public Transportation*, 21(1), 92-103.
- Malichová, E., Cornet, Y., & Hudák, M. (2022). Travellers' use and perception of travel time in long-distance trips in Europe. *Travel Behaviour and Society*, 27, 95-106.
- Management Authority for Urban Railways. (2023). The metro line 1. Retrieved from maur.hochiminhcity.gov.vn/web/en/metro-line-1
- Matsangas, P., & Shattuck, N.L. (2021). Habitability in berthing compartments and well-being of sailors working on US Navy surface ships. *Human factors*, 63(3), 462-473. doi:10.1177/0018720820906050

- Ministry of Infrastructure and Water Management, Province of Zuid-Holland, Noord-Holland, Noord-Brabant, Gelderland, Utrecht, . . . ProRail. (2019). *Public Transport in 2040: Outlines of a vision for the future*. The Hague, the Netherlands: Ministry of Infrastructure and Water Management. Retrieved from <https://www.government.nl/binaries/government/documenten/publications/2019/06/13/public-transport-in-2040-outlines-of-a-vision-for-the-future/Public+Transport+in+2040.pdf>.
- OECD/European Commission. (2020). *Cities in the World: A New Perspective on Urbanisation*. Paris, France: OECD Publishing doi:doi.org/10.1787/05384b8c-en
- Park, H., Khattak, Z., & Smith, B. (2018). *Glossary of Connected and Automated Vehicle Terms*. Retrieved from <https://www.eckertseamans.com/app/uploads/Glossary-of-Connected-and-Automated-Vehicle-Terms-Ver.-1.0-prepared-by-the-University-of-Virginia-Center-for-Transportation-Study.pdf>
- Parker, R.S., & Parker, P. (2017). The impact of sleep deprivation in military surgical teams: a systematic review. *BMJ Military Health*, 163(3), 158-163. doi:10.1136/jramc-2016-000640
- PWC. (2023). The future of mobility. Retrieved from <https://www.pwc.nl/en/industries/automotive/the-future-of-mobility.html>
- Rapid Transition Alliance. (2022, 18 May). European sleeper trains are waking up. Retrieved from <https://rapidtransition.org/stories/european-sleeper-trains-are-waking-up/>
- Rijkswaterstaat. (2023). Sustainable Mobility. Retrieved from <https://www.rijkswaterstaat.nl/en/mobility/sustainable-mobility>
- Rössger, P. (2023, 13-06-2023). HMI or no HMI: The future of humans and displays in electric vehicles. Paper presented at the Automotive Circle, Bad Nauheim, Germany.
- SAE International. (2021). Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles J3016_202104. In. USA and Switzerland: SAE International.
- Sammonds, G.M., Fray, M., & Mansfield, N.J. (2017). Effect of long term driving on driver discomfort and its relationship with seat fidgets and movements (SFMs). *Applied ergonomics*, 58, 119-127.
- Sammonds, G.M., Mansfield, N.J., & Fray, M. (2017). Improving long term driving comfort by taking breaks—How break activity affects effectiveness. *Applied ergonomics*, 65, 81-89. doi:10.1016/j.apergo.2017.05.008
- Schultheis, U. (2016, March 23rd).
- Simons, M., & Spencer, M. (2007). *Extension of flying duty period by in-flight relief*. (TNO-DV 2007 C362). Soesterberg: TNO Defence, Security and Safety
- SMTC. (2014). Reducing the weight of aircraft interiors. *Reinforced Plastics*, 58(4), 36-37. doi:doi.org/10.1016/S0034-3617(14)70180-8
- Smulders, M. (2018). *Flex and relax: An exploration on headrest design for sleeping and watching IFE in premium aircraft seats*. (Industrial Design Engineering Master thesis), Delft University of Technology, Delft. Retrieved from <http://resolver.tudelft.nl/uuid:4e929659-63d7-4816-82b0-a35cd20725ea>

- Smulders, M., Berghman, K., Koenraads, M., Kane, J., Krishna, K., Carter, T., & Schultheis, U. (2016). Comfort and pressure distribution in a human contour shaped aircraft seat (developed with 3D scans of the human body). *WORK*, 54(4), 925-940.
- Smulders, M., & Vink, P. (2021). Human behaviour should be recorded in (dis)comfort research. *WORK*, 68(S1), S289-S294. doi:10.3233/WOR-208027
- Sneddon, A., Mearns, K., & Flin, R. (2013). Stress, fatigue, situation awareness and safety in offshore drilling crews. *Safety Science*, 56, 80-88. doi:10.1016/j.ssci.2012.05.027
- Snider, S.R. (2016, June).
- Societe du Grand Paris. (2023). Grand Paris Express. Retrieved from www.societedugrandparis.fr
- Stanglmeier, M.J., Paternoster, F.K., Paternoster, S., Bichler, R.J., Wagner, P.-O., & Schwirtz, A. (2020). Automated driving: A biomechanical approach for sleeping positions. *Applied ergonomics*, 86, 103103.
- State Government of Victoria. (2023). Suburban Rail Loop. Retrieved from suburbanrailloop.vic.gov.au
- Stevens, S.C., & Parsons, M.G. (2002). Effects of motion at sea on crew performance: a survey. *Marine technology and SNAME news*, 39(01), 29-47. doi:10.5957/mt.2002.39.1.29
- Tadros, M., Ventura, M., & Soares, C.G. (2023). Review of current regulations, available technologies, and future trends in the green shipping industry. *Ocean Engineering*, 280, 114670. doi:10.1016/j.oceaneng.2023.114670
- United Nations Department of Economic Social Affairs - Population Division. (2022). *World Population Prospects 2022: Summary of Results*. UN DESA/POP/2022/TR/NO. 3.
- Vink, P., Anjani, S., Smulders, M., & Hiemstra-van Mastrigt, S. (2017). Comfort and discomfort effects over time: the sweetness of discomfort and the pleasure towards of the end. Paper presented at the 1st International Comfort Congress.
- Vink, P., Rotte, T., Anjani, S., Percuoco, C., & Vos, R. (2020). Towards a hybrid comfortable passenger cabin interior for the flying V aircraft. *International Journal of Aviation, Aeronautics, and Aerospace*, 7(1). doi:10.15394/ijaaa.2020.1431
- Vink, P., Vledder, G., Monteiro, L., & Song, Y. (2022). Passenger reasons for mobility transition from jet to train and turboprop. *Aeronautics and Aerospace Open Access Journal*, 6(4), 118-121. doi:10.15406/aaaj.2022.06.00150
- Weinger, M.B., & Ancoli-Israel, S. (2002). Sleep deprivation and clinical performance. *Jama*, 287(8), 955-957. doi:10.1001/jama.287.8.955
- Wilson, C., Gyi, D., Morris, A., Bateman, R., & Tanaka, H. (2022). Non-Driving Related tasks and journey types for future autonomous vehicle owners. *Transportation research part F: traffic psychology and behaviour*, 85, 150-160.

Part 1

(DIS)COMFORT AND HUMAN BEHAVIOUR

Part 1 discusses factors that influence human behaviour and their effect on (dis)comfort experience in vehicles. Chapter 2 argues human behaviour should be recorded in (dis)comfort research, as otherwise major impacting factors like context, task/activity, posture, movement, stimuli and time might be missed. Recording the behaviour allows for better evaluation and comparison between studies. Chapter 3 is a literature comparison on the effects of time on (dis)comfort, and hypothesises the effect of knowing the end of a situation is near impacts (dis)comfort ratings towards the end of a travel exercise.

HUMAN BEHAVIOUR SHOULD BE RECORDED IN (DIS)COMFORT RESEARCH

This chapter has been published as:

Smulders, M., & Vink, P. (2021). Human behaviour should be recorded in (dis)comfort research. *Work*, 68(s1), S289-S294.

ABSTRACT

(Dis)comfort research that has no information on behaviour of the participants can be considered as incomplete, as major influencing factors could be missed. For (dis)comfort research it is important to capture factors such as context, task/activity, posture, movement, (distracting) stimuli and time, as these factors have influence on the experienced (dis)comfort. Recording the behaviour allows for better evaluation of and comparison between studies, contributing to an increase of scientific knowledge on (dis)comfort.

2.1. Introduction

“Research that has no information on behaviour of the participants can be considered as incomplete as major influencing factors could be missed.” This might sound like a bold statement, but there is evidence that the way humans behave during and prior to an experiment does influence the outcomes. For example, a straight spine in the sagittal plane is sometimes considered ideal for sleeping (Haex, 2004) (see Figure 2.1), but the actual behaviour of humans in bed asks for many other ways of support as shown in Figure 2.2, as humans have different preferred postures (Smulders, 2018; Smulders & Vink, 2022) (see Chapter 7) and change posture between 20-40 times a night (Coenen & Kolff, 2011; Haex, 2004; Verhaert et al., 2011).

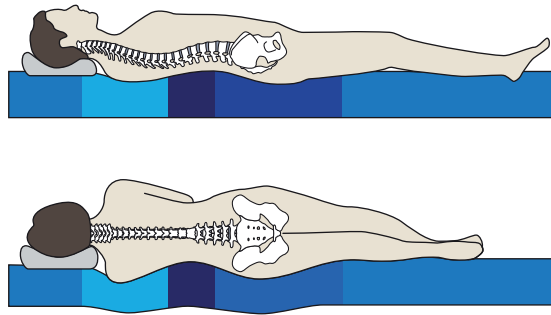


Figure 2.1 | Example of supine and lateral support for a ‘straight’ back. From Smulders (2018b).



Figure 2.2 | Example of the importance of investigating human behaviour in e.g. sleep ergonomics, as people assume different postures and move during sleep. Illustration by Allison Pottasch and Maxim Smulders.

Research in the special issue of WORK (2021) (volume 68, issue s1) on comfort demonstrates that as well. To mention some examples: Califano et al. (2021) stated that task-related upper limb activities are one of the most influential factors in the overall

comfort perception while sitting at a school desk, which shows the importance of recording behaviour influenced by the task. Fiorillo, Anzisi, Carbone, Califano, and Naddeo (2021) studied comfort of library chairs, where comfort decreased over time. So, if you have a searching task in the library for an extensive duration, comfort reduces over time. Sharafkhani, Argyle, Cobb, and Tennent (2021) showed that when aircraft passengers assume a posture with the head rotated more forward, the comfort decreases faster than when having a more upright head, which is in line with previous findings of Smulders et al. (2019) (see Chapter 9). Maybe using a smartphone with the head flexed would result in less comfort than watching the In-Flight Entertainment (IFE) screen while seated in an aircraft seat. Also in an airplane, Torkashvand, Stephane and Vink (2021) asked flight attendants what activities passengers would give a low comfort rating in economy class; sleeping and relaxing were awarded the lowest comfort ratings. Passengers reported the same activities as least comfortable in economy class in a study by Bouwens, Hiemstra-van Mastrigt and Vink (2018a), who found a statistically significant difference in importance of comfort influencing factors for sleeping and watching IFE. Probably sleeping upright or with limited recline is not so comfortable, as sleep efficiency is also lower (Nicholson & Stone, 1987). Additionally, other factors (such as noise, light and smell) than posture influence comfort (Bouwens, et al., 2018a).

2.2. Theoretical explanation

The reason why behaviour influences (dis)comfort is that the experience of (dis)comfort has various behaviour related sources. This experience is partly due to ourselves (e.g. physicality and state of mind), our history and expectations (e.g. previous experiences) and the environment (e.g. stimuli) (Vink, 2014). As it is not the product itself that is comfortable, comfort experience depends on the way the user interacts with the product (Schifferstein & Hekkert, 2008). If we decide to investigate ourselves what our current comfort status is, we will experience some form of (dis)comfort. Thus, the experience of (dis)comfort can also be initiated independent of the environment.

Of course, the environmental context plays a role as well (De Looze, Kuijt-Evers, & Van Dieën, 2003; Desmet & Hekkert, 2007). In most experiments something is changed in the environment and the effect on the human is tested. In the definition of comfort by Vink and Hallbeck (2012) this is clear: *“comfort is seen as a pleasant state or relaxed feeling of a human being in reaction to its environment”*. Whatever the start of the experience of comfort, there is always an initiator, which could be the human or a change in the environment. Then there is a weighing process of all sensory input, after which an unconscious or conscious decision is made on what the level of experienced comfort is. In the sensory input behaviour plays a role, as it determines what the receptors sense, but it can also play a role in the weighing, as distraction could change the (dis)comfort perception and certain actions/context influence the impact of stimuli. In the next paragraphs some examples of these principles will be explained.

2.2.1. Context and activity versus (dis)comfort

In (dis)comfort research it is important to state context and experimental activities, as these have impact on the conducted postures, movement, and the influence of perceived stimuli. E.g. Bouwens, et al. (2018a) showed that context and activity impact the influence of sensory stimuli – such as posture restrictions, noise, smell, climate, vibration and light – on perceived comfort. Smulders et al. (2016) (Chapter 4) show that different activities in a business class aircraft seat result in different postures and thereby influence comfort. Groenesteijn et al. (2012) show this in office seats, Groenesteijn et al. (2014) in train seats and Kamp, Kilincsoy, and Vink (2011) in semi-public spaces and in transit. As shown by Ahmadpour, Kühne, Robert, and Vink (2016), also proximity to other people influences the comfort experience (see Figure 2.3).

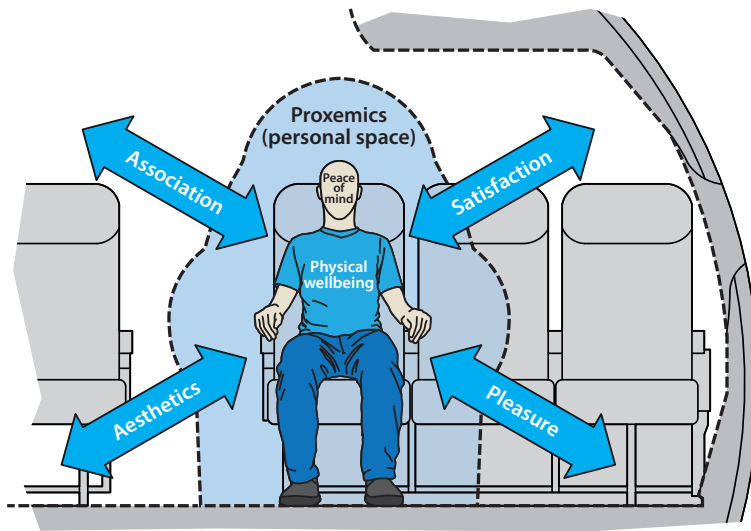


Figure 2.3 | Example of the relation between context features and passenger comfort. From Ahmadpour, Lindgaard, Robert, and Pownall (2014).

2.2.2. Posture versus (dis)comfort

In (dis)comfort research it is important to state the observed postures, as they have impact on perceived (dis)comfort. E.g. Kilincsoy (2019) recorded the comfort of passengers in the rear seat of a car and showed that, in some parts of the body, the upright posture had lower comfort scores than the more relaxed posture. Apostolico, Cappetti, D'Oria, Naddeo, and Sestri (2014) showed that the more neutral the posture is, the more comfortable the posture is rated (see Figure 2.4). Smulders et al. (2019) (see Chapter 9) suggest that humans tend to seek a neutral posture with minimal muscle strain, minimal use of energy and minimal discomfort.

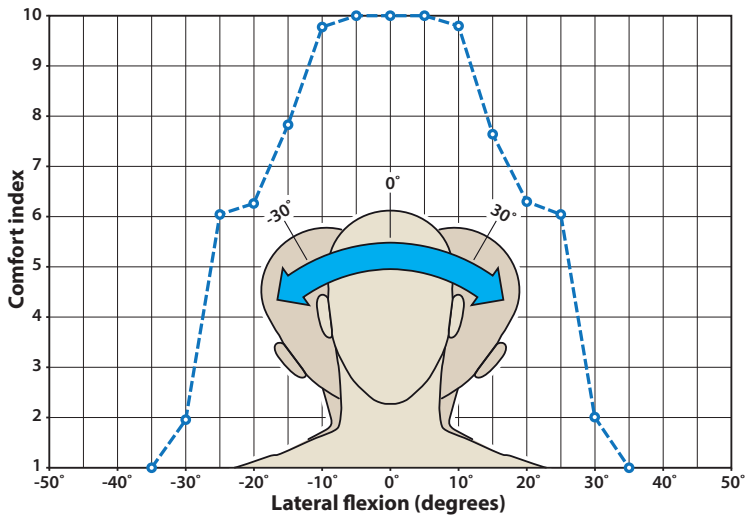


Figure 2.4 | Relation between head angle (posture) and comfort, showing the comfort rating (10-point scale) for degrees of lateral flexion of the head ($n=100$). From Naddeo (2017), based on Apostolico et al. (2014).

2.2.3. Movement versus (dis)comfort

In (dis)comfort research it is important to state movement observations, as they have impact on the perceived (dis)comfort. E.g. Sammonds, Fray, and Mansfield (2017) show there is a correlation between movements and perceived discomfort, where more movement is correlated with more perceived discomfort (see Figure 2.5). Similar results were observed by Le, Rose, Knapik, and Marras (2014) and Bouwens, et al. (2018b). Hiemstra-van Mastrigt, Kamp, Van Veen, Vink, and Bosch (2015) and Bouwens, et al. (2018c) showed that stimulating in-seat movement improved comfort. Van Veen, Orlinskiy, Franz, and Vink (2015) showed that a slow passive movement of the backrest and seat pan that is hardly noticeable has a positive impact on comfort as well. For an active movement system, Franz, Zenk, Vink, and Hallbeck (2011) showed that a massage system in the backrest increased comfort and reduced muscle activity in the neck. Also Van Dieën, De Looze, and Hermans (2001) suggest that dynamic office chairs offer a potential advantage over fixed chairs, as dynamic seats lower spinal shrinkage.

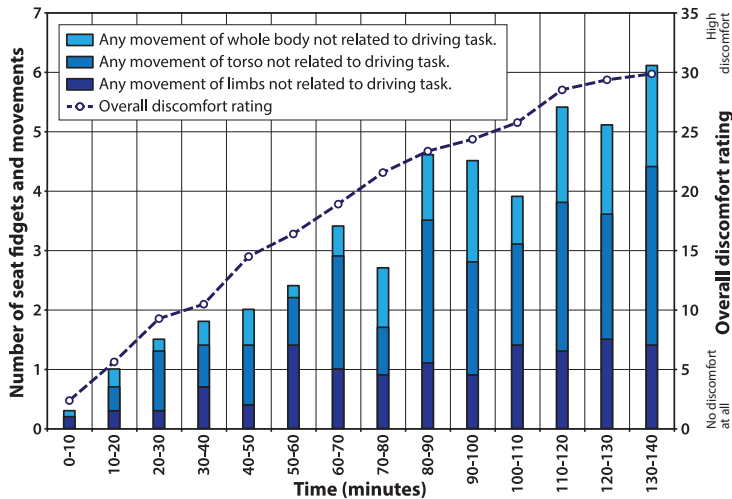


Figure 2.5 | Example of the relation of movement and discomfort (Borg CR100 scale), showing the mean overall discomfort rating and number of seat fidgets and movements (SFMs) against time for all participants ($n=10$). From Sammonds et al. (2017).

2.2.4. Previous conditions and expectations versus (dis)comfort

In (dis)comfort research it is important to state the pre-test conditions, as they might have impact on perceived (dis)comfort. E.g. Van Veen and Vink (2016) showed that prior seating conditions (a hard or soft seat surface) significantly influence the experienced seat comfort, as sitting on a hard surface in the precondition made the next seat feel softer. Roelofsen (2016) described that when one is exposed to a broader range of temperatures during their lifetime, the range of temperatures one considers comfortable is broader as well. That said, humans are bad at noticing gradual changes over time (Goossens, Teeuw, & Snijders, 2005). Also participant expectations play a role, as shown in an experiment by Naddeo, Cappetti, Califano, and Vallone (2015) where participants rated a mattress of which they were told that it was very expensive as more comfortable than the exact same mattress of which they were told that it was cheap. Participants' initial comfort expectations can also contradict the actual experienced comfort. Bouwens, et al. (2018b) show this in travel pillows, where an “*embrace sleep collar*” (which restricts head movement) was visually rated least comfortable, but rated as most comfortable after actual use.

2.2.5. (Distracting) stimuli versus (dis)comfort

In (dis)comfort research it is important to state the stimuli, as they might have impact on perceived (dis)comfort. E.g. Hiemstra-van Mastrigt, Meyenborg, and Hoogenhout (2016) and Bouwens, Tsay, and Vink (2017) showed that distractions such as meal services (see Figure 2.6) and walking breaks during long-haul flights lowered the experienced discomfort and increased passengers' positive emotional level. Lewis et al. (2016) showed that with a VR entertainment system, passengers can be distracted from discomfort caused by a lack of knee space. In addition, Hiemstra-van Mastrigt et al. (2016) showed that interaction with other people could also distract from discomfort.

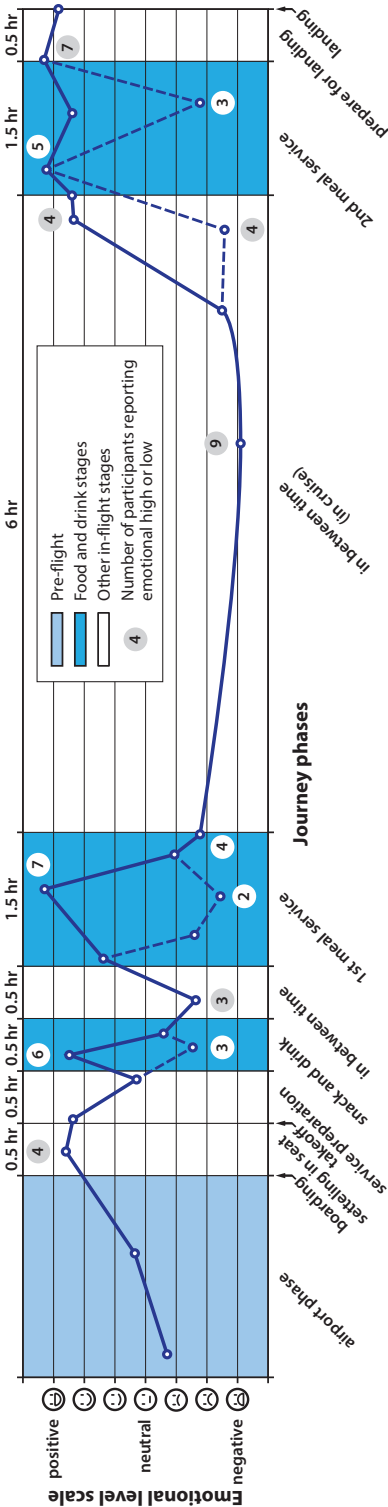


Figure 2.6 | Example of impact of stimuli on emotional level (7-point scale), showing the emotional timeline of passengers during flight (n=9). The solid line shows the overall emotion level of participants during the flight and the dashed line shows the number of participants reporting high or low emotions. The numbers in the bubbles represent the number of participants that reported their emotions similarly. From Bouwens et al. (2017).

2.2.6. Time versus (dis)comfort

In (dis)comfort research it is important to state the duration, as time has impact on perceived (dis)comfort. E.g. Vink, Anjani, Smulders, and Hiemstra-van Mastrigt (2017) (see Chapter 3) show in their literature comparison that generally comfort decreases over time (see Figure 2.7) and discomfort increases over time (see Figure 2.5) when conducting the same activity. Being aware of ‘*the end*’ of an activity will influence the comfort perception as well. Prolonged sitting in an aircraft and being aware that the landing procedure will start soon, can actually increase comfort (see Figure 2.8). Thus, participants being aware of the time and duration of an activity can actually influence test results. E.g. Sammonds, Fray, and Mansfield (2014) discuss that drivers adjust their behaviour over time to cope with discomfort.

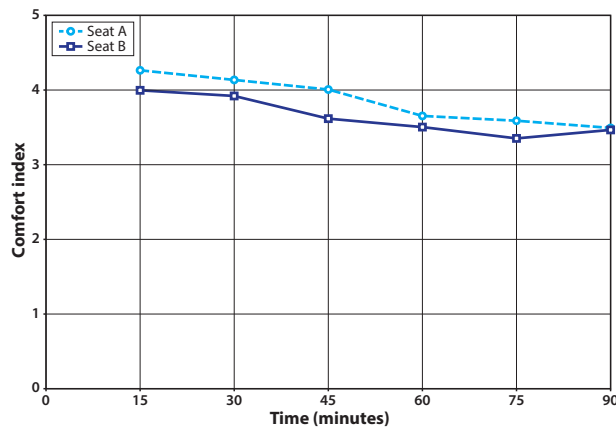


Figure 2.7 | Example of change of comfort (6-point scale) over time of business class passenger in two different business class seats: a reference seat and a prototype seat based on the human contour (n=20). Graph plotted based on data of Smulders et al. (2016) (Chapter 4).

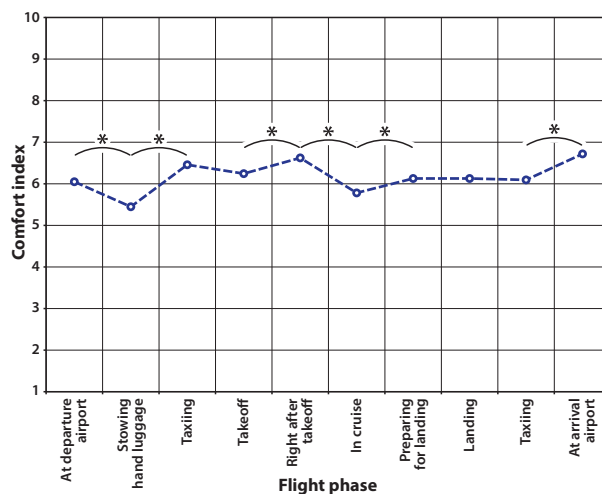


Figure 2.8 | Example of change of comfort (10-point scale) over time (n=149). From De Lille, Santema, Bouwens, Schultheis, and Vink (2016) and Bouwens et al. (2017).

2.3. Conclusion

It is important in (dis)comfort research to indicate what participants did before participating in the test (prior activities), how they move/behave during the test, what postures they assume and whether there are stimuli used that distract or influence the behaviour. In addition, the duration of activities and stimuli (and the fact of the participant being aware or not of time and the end of activities/stimuli) should be captured as well, as these all have impact on the experienced (dis)comfort. Reporting these factors allows for better evaluation and comparison of comfort research results, which should contribute to an increase of scientific knowledge on (dis)comfort.

2.4. Acknowledgements

The authors would like to thank Allison Pottasch for allowing to use one of her great illustrations, and prof. Alessandro Naddeo, prof. Neil Mansfield and dr. Naseem Ahmadpour for allowing us to use their graphs in this publication. In addition, the authors would like to acknowledge the contributions of the cited authors to the scientific field on comfort.

2.5. References

- Ahmadpour, N., Kühne, M., Robert, J.M., & Vink, P. (2016). Attitudes towards personal and shared space during the flight. *Work*, 54(4), 981-987. doi: 10.3233/wor-162346
- Ahmadpour, N., Lindgaard, G., Robert, J.M., & Pownall, B. (2014). The thematic structure of passenger comfort experience and its relationship to the context features in the aircraft cabin. *Ergonomics*, 57(6), 801-815. doi:10.1080/00140139.2014.899632
- Apostolico, A., Cappetti, N., D'Oria, C., Naddeo, A., & Sestri, M. (2014). Postural comfort evaluation: experimental identification of Range of Rest Posture for human articular joints. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 8(2), 109-120. doi:10.1007/s12008-013-0186-z
- Bouwens, J.M.A., Fasulo, L., Hiemstra-van Mastrigt, S., Schultheis, U.W., Naddeo, A., & Vink, P. (2018c). Effect of in-seat exercising on comfort perception of airplane passengers. *Applied ergonomics*, 73, 7-12. doi: 10.1016/j.apergo.2018.05.011
- Bouwens, J.M.A., Hiemstra-van Mastrigt, S., & Vink, P. (2018a). Ranking of human senses in relation to different in-flight activities contributing to the comfort experience of airplane passengers. *International Journal of Aviation, Aeronautics, and Aerospace*, 5(2), 9. doi: 10.15394/ijaaa.2018.1228
- Bouwens, J.M.A., Schultheis, U.W., Hiemstra-van Mastrigt, S., & Vink, P. (2018b). Expected versus experienced neck comfort. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 28(1), 29-37. doi: 10.1002/hfm.20721

- Bouwens, J.M.A, Tsay, W.J.J., & Vink, P. (2017). The high and low comfort peaks in passengers' flight. *Work*, 58(4), 579-584. doi: 10.3233/wor-172637
- Califano, R., Cecco, M., de Cunzio, G., Napolitano, N., Rega, E., Fiorillo, I., & Naddeo, A. (2021). School combo-desk comfort assessment: a method for weighting postural factors that affect the overall perceived comfort. *Work(S1)*, S47–S57.
- Coenen, A.M.L., & Kolff, M. (2011). Body postures in sleep. In *Sleep-Wake* (Vol. 22, pp. 44-47). Annual Proceedings of the NSWO (Dutch Society for Sleep-Wake Research).
- De Lille, C., Santema, S., Bouwens, J.M., Schultheis, U., & Vink, P. (2016). Designing the cabin interior knowing high and low peaks in a passenger flight. Paper presented at the AEGATS Conference Paris, abstract nr AEGATS2016_48.
- De Looze, M.P., Kuijt-Evers, L.F., & Van Dieen, J. (2003). Sitting comfort and discomfort and the relationships with objective measures. *Ergonomics*, 46(10), 985-997. doi:10.1080/0014013031000121977
- Desmet, P., & Hekkert, P. (2007). Framework of product experience. *International journal of design*, 1(1), 57-66. doi: <http://ijdesign.org/index.php/IJDesign/article/view/66>
- Fiorillo, I., Anzisi, F.J., Carbone, A., Califano, R., & Naddeo, A. (2021). A method for postural critical factors checking: the case of library chairs. *Work*, 68(S1), S87–S100.
- Franz, M., Zenk, R., Vink, P., & Hallbeck, S. (2011). The effect of a lightweight massage system in a car seat on comfort and electromyogram. *Journal of manipulative and physiological therapeutics*, 34(2), 107-113. doi:10.1016/j.jmpt.2010.12.002
- Goossens, R.H.M., Teeuw, R., & Snijders, C.J. (2005). Sensitivity for pressure difference on the ischial tuberosity. *Ergonomics*, 48(7), 895-902.
- Groenesteijn, L., Ellegast, R.P., Keller, K., Krause, F., Berger, H., & de Looze, M.P. (2012). Office task effects on comfort and body dynamics in five dynamic office chairs. *Applied ergonomics*, 43(2), 320-328. doi: 10.1016/j.apergo.2011.06.007
- Groenesteijn, L., Hiemstra-van Mastrigt, S., Gallais, C., Blok, M., Kuijt-Evers, L., & Vink, P. (2014). Activities, postures and comfort perception of train passengers as input for train seat design. *Ergonomics*, 57(8), 1154-1165.
- Haex, B. (2004). Back and bed: ergonomic aspects of sleeping. Boca Raton, FL, USA: CRC press. doi:10.1201/9780203022306
- Hiemstra-van Mastrigt, S., Kamp, I., Van Veen, S.A.T., Vink, P., & Bosch, T. (2015). The influence of active seating on car passengers' perceived comfort and activity levels. *Applied ergonomics*, 47, 211-219. doi: 10.1016/j.apergo.2014.10.004
- Hiemstra-van Mastrigt, S., Meyenborg, I., & Hoogenhout, M. (2016). The influence of activities and duration on comfort and discomfort development in time of aircraft passengers. *WORK*, 54(4), 955-961.
- Kamp, I., Kilincsoy, Ü., & Vink, P. (2011). Chosen postures during specific sitting activities. *Ergonomics*, 54(11), 1029-1042.
- Kilincsoy, Ü. (2019). *Digitalization of posture-based Seat Design*. (Doctoral Dissertation), Delft University of Technology, Delft, The Netherlands. doi:10.4233/uuid:419e4678-cb27-4c03-9725-7fb5b0fd3a12

- Le, P., Rose, J., Knapik, G., & Marras, W.S. (2014). Objective classification of vehicle seat discomfort. *Ergonomics*, 57(4), 536-544. doi: 10.1080/00140139.2014.887787
- Lewis, L., Patel, H., Cobb, S., D'cruz, M., Bues, M., Stefani, O., & Grobler, T. (2016). Distracting people from sources of discomfort in a simulated aircraft environment. *WORK*, 54(4), 963-979. doi:10.3233/WOR-162356
- Naddeo, A. (2017). *Towards predicting the (dis)comfort performance by modelling: methods and findings*. (PhD thesis), Delft University of Technology, Delft. doi: 10.4233/uuid:ac8ebee1-278c-484d-acc0-d39c765c1ac2
- Naddeo, A., Cappetti, N., Califano, R., & Vallone, M. (2015). The role of expectation in comfort perception: the mattresses' evaluation experience. *Procedia Manufacturing*, 3, 4784-4791.
- Nicholson, A., & Stone, B.M. (1987). Influence of back angle on the quality of sleep in seats. *Ergonomics*, 30(7), 1033-1041.
- Roelofsen, C.P.G. (2016). *Modelling relationships between a comfortable indoor environment, perception and performance change*. (PhD thesis), Delft University of Technology, Delft. doi: 10.4233/uuid:e7778a5c-3013-40ed-9567-bceaffc57ab9
- Sammonds, G.M., Fray, M., & Mansfield, N. (2014). Overall car seat discomfort onset during long duration driving trials. Paper presented at the Advances in Physical Ergonomics and Human Factors Part II, AHFE Conference Books.
- Sammonds, G.M., Fray, M., & Mansfield, N.J. (2017). Effect of long term driving on driver discomfort and its relationship with seat fidgets and movements (SFM). *Applied ergonomics*, 58, 119-127.
- Schifferstein, H.N.J., & Hekkert, P. (2008). Product experience. Oxford, UK: Elsevier. doi: 10.1016/B978-0-08-045089-6.X5001-1
- Sharafkhani, M., Argyle, E., Cobb, S., & Tennent, P. (2021). Posture, Movement, and Aircraft Passengers: An Investigation into Factors Influencing In-Flight Discomfort. *Work*, 68(S1), S183-S195.
- Smulders, M. (2018). *Flex and relax: an exploration on headrest design for sleeping and watching IFE in premium aircraft seats*. (Master thesis), Delft University of Technology, Delft. Retrieved from <http://resolver.tudelft.nl/uuid:4e929659-63d7-4816-82b0-a35cd20725ea>
- Smulders, M., Berghman, K., Koenraads, M., Kane, J.A., Krishna, K., Carter, T.K., & Schultheis, U. (2016). Comfort and pressure distribution in a human contour shaped aircraft seat (developed with 3D scans of the human body). *Work*, 54(4), 925-940. doi: 10.3233/wor-162363
- Smulders, M., Naddeo, A., Cappetti, N., van Grondelle, E., Schultheis, U., & Vink, P. (2019). Neck posture and muscle activity in a reclined business class aircraft seat watching IFE with and without head support. *Applied ergonomics*, 79, 25-37. doi: 10.1016/j.apergo.2018.12.014
- Smulders, M., & Vink, P. (2022). Sleeping postures in adults: a literature review. Paper presented at the 21st Triennial Congress of the International Ergonomics Association.

- Torkashvand, G., Stephane, L., & Vink, P. (2021). Perceived onboard passengers' experience: flight attendants' point of view. *Work*, 68(S1), S239–S243.
- Van Dieën, J.H.L., De Looze, M.P., & Hermans, V. (2001). Effects of dynamic office chairs on trunk kinematics, trunk extensor EMG and spinal shrinkage. *Ergonomics*, 44(7), 739–750. doi: 10.1080/00140130120297
- Van Veen, S., Orlinskiy, V., Franz, M., & Vink, P. (2015). Investigating car passenger well-being related to a seat imposing continuous posture variation. *Journal of Ergonomics*, 4, 140. doi: 10.4172/2165-7556.1000140
- Van Veen, S., & Vink, P. (2016). Can prior experience influence seating comfort ratings? *ergonomics in design*, 24(2), 16-20.
- Verhaert, V., Haex, B., De Wilde, T., Berckmans, D., Vandekerckhove, M., Verbraecken, J., & Vander Sloten, J. (2011). Unobtrusive assessment of motor patterns during sleep based on mattress indentation measurements. *IEEE Transactions on Information Technology in Biomedicine*, 15(5), 787-794. doi:10.1109/TITB.2011.2131670
- Vink, P. (2014). *The sweetness of discomfort: Designing the journey*. (Inaugural address), Delft University of Technology, Delft, The Netherlands. Retrieved from <http://resolver.tudelft.nl/uuid:517db1ea-9e10-4ba7-9bae-f012698eddb3>
- Vink, P., Anjani, S., Smulders, M., & Hiemstra-van Mastrigt, S. (2017). Comfort and discomfort effects over time: the sweetness of discomfort and the pleasure towards of the end. Paper presented at the 1st International Comfort Congress.
- Vink, P., & Hallbeck, S. (2012). Comfort and discomfort studies demonstrate the need for a new model. *Applied ergonomics*, 43(2), 271-276. doi: 10.1016/j.apergo.2011.06.001

COMFORT AND DISCOMFORT EFFECTS OVER TIME

THE SWEETNESS OF DISCOMFORT AND THE PLEASURE TOWARDS THE END

This chapter has been published as:

Vink, P., Anjani, S., Smulders, M., & Hiemstra-van Mastrigt, S. (2017). Comfort and discomfort effects over time: the sweetness of discomfort and the pleasure towards of the end. In *1st International Comfort Congress*, Salerno, Italy.

ABSTRACT

In this chapter the influence of time on comfort and discomfort is studied. An unpleasant experience could make a person more aware of their (dis)comfort in the next event. The hypothesis is that a situation with discomfort could result in less discomfort near the end as the participant is or becomes aware of the fact that the situation (and experienced discomfort) will end soon.

A secondary analysis of six studies, where (dis)comfort over time is studied, showed some support for the hypothesis. The six studies show comfort decreases and discomfort increases over time. Three studies show a reduction in discomfort near the end, the others were difficult to interpret. Further research is needed to affirm the hypothesis.

3.1. Introduction

There is at least one thing on which passengers or end-users have more knowledge than comfort researchers and comfort designers (Vink & Brauer, 2011). That is the passengers' own sense of comfort or the end-users' own sense of comfort. Researchers and designers cannot predict exactly whether a particular passenger feels comfortable in an airplane or whether an end-user will feel comfortable using the product. This is due to the fact that apart from the product or system that is designed many factors influence comfort. The mood of the participant has its influence, but also factors that are not always influenced by the product or system itself (Vink, 2014; Vink & Hallbeck, 2012). A comfortable indoor temperature is dependent on the outside temperature (de Dear & Brager, 2002). And, a nice flight attendant can create comfort and make passengers forget about the hard seat (Vink, Bazley, Kamp, & Blok, 2012). Even a VR system with an attractive game can reduce the discomfort caused by limited leg space (Lewis et al., 2016). This seems a bit frustrating for designers of products and systems focussed on more comfort.

However, on group level effects can be predicted and a good design will have its effects. The study of 10,000 passengers reported in Vink et al. (2012) showed that newer planes are regarded significantly better with respect to comfort than older planes. These findings should give those involved in the airline industry a sense of satisfaction, with regard to the job they have done in improving comfort. They have shown that it is possible to improve the comfort experience. Another more specific example that shows comfort can be influenced is the study of Bronkhorst and Krause (2004). They studied the whole train journey and determined which activities are conducted in the train seat. They adapted the train seat to the activities to create a comfortable experience. These activity supporting train seats were designed for the commuter train '*Long Island Railroad*', bringing passengers from Long Island to New York (Bronkhorst & Krause, 2004). It appeared that 83% of the passengers preferred the resulting seat to current seats and the comfort was rated higher.

There is another opportunity to improve the comfort experience. That is making use of the principle of the '*sweetness of discomfort*' (Vink, 2014). The sense of the softness of a seat is dependent on the hardness of the previous seat (Van Veen & Vink, 2016). Van Veen and Vink (2016) showed that after sitting on a hard wooden stool, a test seat feels significantly softer than sitting in a comfortable seat and then sitting on a test seat. In this experiment the test seat was covered with a white blanket and the participants were told that the seat differences would not be shown. In fact, the seat was not changed. This information was not relayed to the test participants. Before the test, participants were instructed to sit on the stool and the luxury seat to become accustomed to the environment. Half of the participants began with the '*hard stool*' conditions and the other half began in the '*luxury soft seat*' condition. At the same time the next day the participants arrived to test the '*second seat*' and the pre-condition was changed again. The results show for the pre-condition '*stool*' (the seat feels soft: 1 = "*I don't agree*", 9 = "*I agree*") a rating of 6.75 ± 1.94 on a 9-point scale, and for the pre-condition '*luxury seat*' a rating of 4.96 ± 2.46 which was significantly different ($p = .012$). So, the theoretical assumption that precondition influences the sensation appears to be true. This can be applied in seat

design, for instance by starting with a hard surface, and that by pushing a button the seat becomes softer. This can be done by using e.g. a Vita Materials' air/foam cushion. This cushion is filled with air and rather hard. At the touch of a button the valve design allows the passenger's weight to exhaust the air from the cushion and provide a personalised contoured seat. This distributes weight evenly and it could be more comfortable than the previous hard state. It would be interesting to study this hypothesis.

As shown by Van Veen and Vink (2016), sitting on a hard surface in the precondition could make the tested seat feel softer. For other senses the principle of influence by the previous experience is described as well. Temperature is experienced differently when coming into an interior from a cold environment as opposed to coming in from a warm environment (De Dear & Brager, 2002). Retreating in and out of dark and light spaces influences our senses. Our senses see the interior of an airplane differently when emerging from a dark jet way than when entering the airplane by stairs in open air (Vink, 2014). Konieczny (2001) found that comfort during the flight correlated most with the comfort preceding the flight ($r = .407$), fear of flying ($r = .492$), and attitude toward flying ($r = .367$). Correlations to other factors were weaker. This study infers that situations or experiences before the flight could influence the experience during the flight.

Making all steps in the journey highly comfortable probably does not automatically make the whole journey comfortable, because the human senses record differences better than absolute values (Goossens, Teeuw, & Sniijders, 2005; Helander, Little, & Drury, 2000; Vink, 2014). Perhaps phases of discomfort or low comfort should be alternated with more comfortable phases in order to stimulate more awareness of high comfort or low discomfort levels: "*the sweetness of discomfort*" (Vink, 2014). Of course, the discomfort should not be so high that it makes the whole journey a terrible experience. Introducing a bed of sharp nails or introducing sounds above the pain level is not advised as an object of study. The challenge is to find the ideal balance between comfort and discomfort experiences for the entire travel journey.

Apart from the influence of the phase at the beginning of the comfort experience, the end phase also has opportunities for comfort increase. The study of Kahneman et al. (1993) showed that at the end of a pain period, the human experience can be improved by adding a phase where the pain is slowly reduced. This resulted in a better experience than when the situation was immediately ended. The study also showed that the discomfort experience reduced towards the end in both situations, while the condition was the same. The question is whether the findings of this pain experiment are valid for long-term comfort and discomfort studies as well. Therefore, in this chapter a few recent studies with long-term comfort experiments where data was gathered over time are investigated. The hypothesis is that in a situation where comfort is low or discomfort is high, the discomfort reduces towards the end of the experiment or the comfort increases near the end.

3.2. Methods

To test the hypothesis, a secondary analysis was performed on six studies mentioned in five journal papers with data on comfort or discomfort over time. These studies were selected as their data were available. A study of De Lille, Santema, Bouwens, Schultheis, and Vink (2016) on comfort during a flight, a study of Sammonds, Fray, and Mansfield (2017) on discomfort while sitting 140 minutes in a car seat, a study of Smulders et al. (2016) (Chapter 4) on comfort while sitting 90 minutes in a business class aircraft seat, a study of Li, Yu, Yang, Pei, and Zhao (2017) on discomfort while sitting 3 hours on a seat simulating a 28", 30" and 32" pitch, and two studies of Bazley, Nugent, and Vink (2015) on discomfort during the workweek. De Lille et al. (2016) asked 149 travellers on the comfort of their last flight on a scale from 1-10 (10 being the maximum comfort) and they calculated the average. Sammonds et al. (2017) used an adapted Borg CR100 scale (Borg & Borg, 2002; Mansfield, Sammonds, & Nguyen, 2015) and studied 10 participants in the driving positions in a driving simulator and calculated the average. Smulders et al. (2016) (Chapter 4) studied 12 participants sitting 90 minutes in two types of business class seats. In the secondary analysis the average comfort is calculated over the 12 participants and the two conditions of the Smulders' study. In the study of Li et al. (2017) the discomfort was recorded in 18 healthy participants seated for three hours in three different seat pitches (32", 30" and 28"). A seat pitch is the distance from a point on a seat to the exact same point on the seat in front. A 28" pitch is usually a situation where there is limited legroom, although that is dependent on the thickness of the backrest as well. The Body Part Discomfort Scale described by Corlett and Bishop (1976) was used in this study. Bazley et al. (2015) studied the discomfort in a workweek in two professions: 16 engineering professionals located in the USA with a workweek of 4 days and 18 plasterers located in Ireland with a workweek of 5 days. The comfort was recorded 3 times a day for the engineers and four times a day for the plasterers, and the values of the different participants were averaged.

3.3. Results and discussion

Based on the hypothesis, the comfort would raise or the discomfort would reduce near the end of an activity. Out of the six figures based on the five afore mentioned papers describing the (dis)comfort pattern over time, three affirm the hypothesis. In the other three it is less clear. In Figure 3.1 the comfort increases at the end where passengers know that they approach the destination. In Figure 3.5 the discomfort reduces during the last workday and Figure 3.6 also shows a reduction after Thursday, as the plasterers know that the end of the workweek is approaching. One study does not affirm the hypothesis, as it shows in Figure 3.3 that the discomfort increases also near the end (although it is tapering off). However, Figure 3.2 shows no further reduction in comfort, which could affirm the hypothesis. But it could also be that the minimum in comfort is reached, which will not further decrease in this business class seat. The discomfort in Figure 3.4 continues to increase for the 28" seat, which is very narrow and has very little leg room. For the 30" and 32" seats, discomfort tapers off past the two-hour mark, which could be caused by the fact that the end of the seating experience is near.

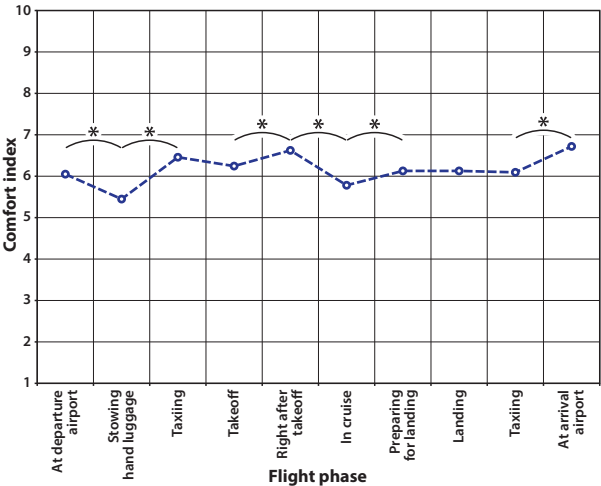


Figure 3.1 | Example of change in comfort (10-point scale) over time (n=149). From De Lille et al. (2016) and Bouwens, Tsay, and Vink (2017).

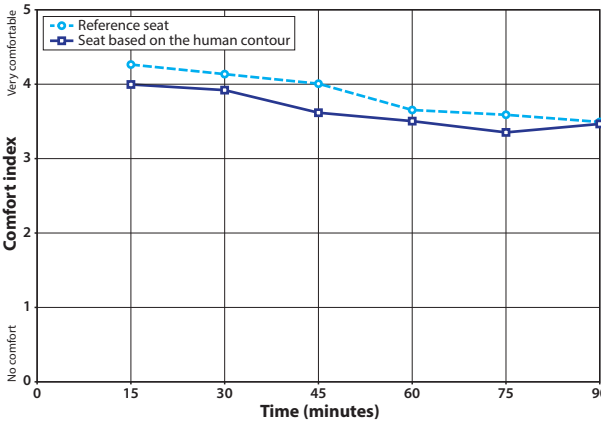


Figure 3.2 | Example of change in comfort (6-point scale) over time of business class passengers in two different business class seats: a reference seat and a prototype seat based on the human contour (n=20). Graph plotted based on data of Smulders et al. (2016) (Chapter 4).

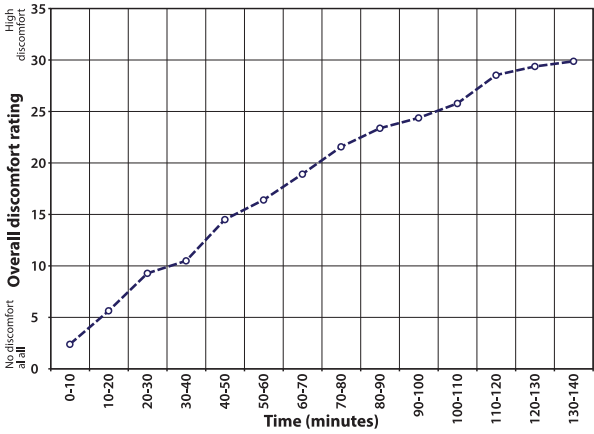


Figure 3.3 | Example of change in mean overall discomfort (Borg CR100 scale) rating while driving in a car simulator against time, of all participants (n=10). From Sammonds et al. (2017).

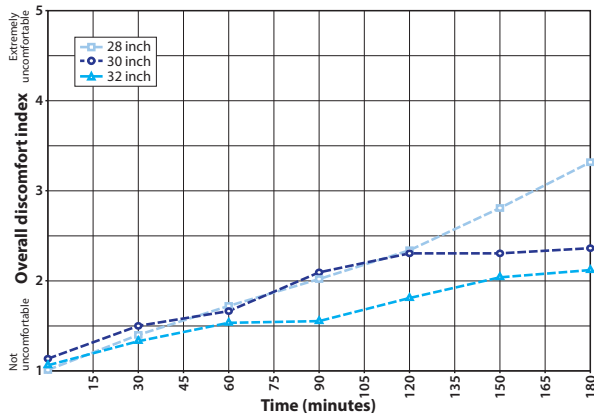


Figure 3.4 | Example of change in mean discomfort (5-point scale) score over time in three seat conditions, of all participants (n=18). From Li et al. (2017).

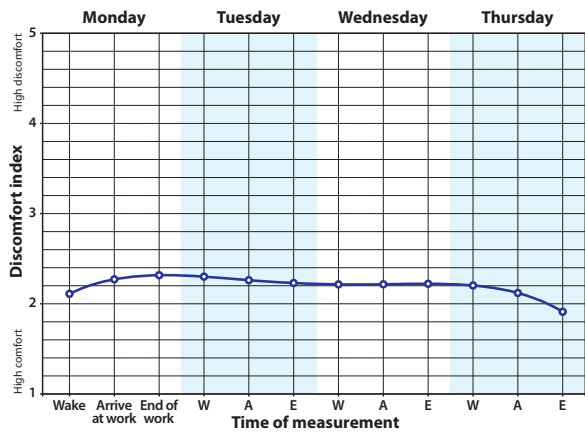


Figure 3.5 | Discomfort of engineers based on a four-day workweek (n=16). W = Waking, A = Arrive at Work, and E = End of Work. From Bazley et al. (2015), based on the work of Bazley, Vink, De Jong, and Hedge (2012).

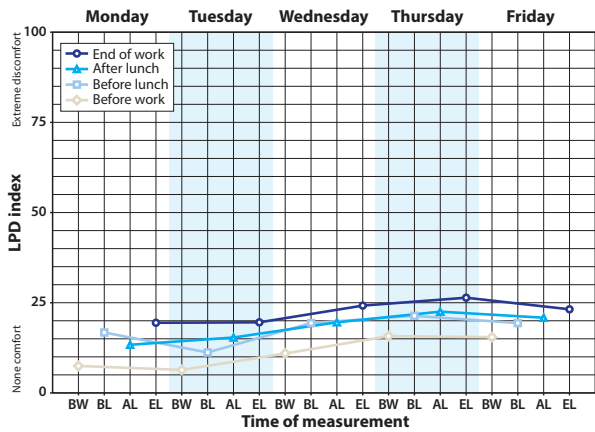


Figure 3.6 | Local Postural Discomfort (LPD) index summed up over all body regions and averaged over physical plasterers (n=18) and at the end of different days in the week as recorded on 100 mm Visual Analogue Discomfort Scales (VADS) scales (0 = “No Discomfort”, 100 = “Extreme Discomfort”). BF = Before Work, BL = Before Lunch, AL = After Lunch, and EW = End of Work. From Bazley et al. (2015), based on the work of Nugent (2012).

Drawing a conclusion from these six studies should be done with care. Statistics on significance is missing and it is not clear whether the participants were aware of the fact that the experiment was almost done near the end. In the case of the workweek and the flight, it is clear that participants knew that the end of the experience is near. However, in the other papers nothing is reported on the fact that people could see a watch/clock or have other information about the end of the test. The fact that the end of an experience is important has been described before (e.g. Fredrickson (2000)). Kahneman, Fredrickson, Schreiber, and Redelmeier (1993) also describe the positive effect associated with hope for a good outcome. Also, the phenomenon regarding comfort has been described before. Bazley and Vink (2016) describe that for students on Friday, before the weekend, the comfort levels were significantly higher than on Thursday, the day before (t-test for paired comparison, $p \leq .05$).

So, this chapter is only an indication that the hypothesis could be true. More research is needed in which different endings should be compared. The comfort in time could be studied of endings where participants are aware of the end compared with those who are not aware of the time the experiment or experience stops. This should have its influence on the comfort experience and (dis)comfort ratings. Even a condition could be added as described in Kahneman et al. (1993) in which the discomfort is slowly reduced instead of immediately stopped. If the hypothesis is true, this has implications for the journey design. For example, in long queues informing the participants at the end could reduce discomfort, and timed information while travelling could be useful as well to manage (expected) comfort. Also slowly reducing the discomfort like in the experiment of Kahneman et al. (1993) could be added. It could be applied in a taxi ride as well. For instance, being in a foreign taxi could create uncertainty of the travel time and create discomfort. This discomfort could perhaps be improved near the end by showing the expected arrival time or the expected travel time. Also, for research this has implications. Preferably the ending time should not be mentioned as it could influence the comfort or discomfort scores, unless it is important to simulate a specific context where being aware of *'the end'* is relevant.

3.4. Conclusion

Comfort and discomfort are influenced by previous experiences and effects over time. There are indications that when a person enters an event the (dis)comfort levels are dependent on where a person has been and what the previous (dis)comfort experience was. An unpleasant experience could make a person more aware of the (dis)comfort in the next event. Also, the end of the event (e.g. an experiment or an event in daily life) could be influenced by expectation of what will happen. A participant/user being aware that the situation will end soon could be of influence on the experienced (dis)comfort.

The hypothesis is that for a situation where comfort is low, the comfort increases near the end. Or in a situation where discomfort is high, the discomfort reduces towards the end. There are indications that the hypothesis is supported by a few studies, but further research is needed to affirm this.

3.5. References

- Bazley, C., Nugent, R., & Vink, P. (2015). Patterns of discomfort. *Journal of Ergonomics*, 5(1), 2015. doi:10.4172/2165-7556.1000136
- Bazley, C., & Vink, P. (2016). Don't forget time in environmental design. *Work*, 54(4), 1025-1029. doi:10.3233/wor-162364
- Bazley, C., Vink, P., De Jong, A., & Hedge, A. (2012). The influence of expectations and pre-experiences on comfort at work. In P. Vink (Ed.), *Advances in social and organizational factors* (pp. 663-671). Boca Raton, FL, USA: CRC Press. doi:10.1201/b12314
- Borg, E., & Borg, G. (2002). A comparison of AME and CR100 for scaling perceived exertion. *Acta psychologica*, 109(2), 157-175. doi:10.1016/S0001-6918(01)00055-5
- Bouwens, J.M., Tsay, W.J.J., & Vink, P. (2017). The high and low comfort peaks in passengers' flight. *Work*, 58(4), 579-584. doi: 10.3233/wor-172637
- Bronkhorst, R., & Krause, F. (2004). Designing comfortable passenger seats. In P. Vink (Ed.), *Comfort and Design* (pp. 173-186). Boca Raton, FL, USA: CRC Press. doi:10.1201/9781420038132.ch13
- Corlett, E.N., & Bishop, R. (1976). A technique for assessing postural discomfort. *Ergonomics*, 19(2), 175-182. doi:10.1080/00140137608931530
- De Dear, R.J., & Brager, G.S. (2002). Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. *Energy and buildings*, 34(6), 549-561. doi:10.1016/s0378-7788(02)00005-1
- De Lille, C., Santema, S., Bouwens, J., Schultheis, U., & Vink, P. (2016). Designing the cabin interior knowing high and low peaks in a passenger flight. Paper presented at the AEGATS Conference Paris, abstract nr AEGATS2016_48, Paris, France.
- Fredrickson, B.L. (2000). Extracting meaning from past affective experiences: The importance of peaks, ends, and specific emotions. *Cognition & Emotion*, 14(4), 577-606. doi:10.1080/026999300402808
- Goossens, R.H.M., Teeuw, R., & Snijders, C.J. (2005). Sensitivity for pressure difference on the ischial tuberosity. *Ergonomics*, 48(7), 895-902.
- Helander, M.G., Little, S.E., & Drury, C.G. (2000). Adaptation and sensitivity to postural change in sitting. *Human factors*, 42(4), 617-629.
- Kahneman, D., Fredrickson, B.L., Schreiber, C.A., & Redelmeier, D.A. (1993). When more pain is preferred to less: Adding a better end. *Psychological science*, 4(6), 401-405.
- Konieczny, G. (2001). Die Messung und Steigerung der Qualität von Dienstleistungen in der Flugzeugkabine-ein Beitrag zur kundenorientierten Flugzeugentwicklung. (Doctoral dissertation), Technische Universität Berlin, Berlin and Frankfurt am Main, Germany. doi:10.14279/depositonce-352
- Li, W., Yu, S., Yang, H., Pei, H., & Zhao, C. (2017). Effects of long-duration sitting with limited space on discomfort, body flexibility, and surface pressure. *International Journal of Industrial Ergonomics*, 58, 12-24. doi:10.1016/j.ergon.2017.01.002

- Mansfield, N., Sammonds, G., & Nguyen, L. (2015). Driver discomfort in vehicle seats—Effect of changing road conditions and seat foam composition. *Applied ergonomics*, 50, 153-159. doi:10.1016/j.apergo.2015.03.010
- Nugent, R. (2012). *Ergonomic analysis of work related musculoskeletal disorder risk to plasterers working in Ireland*. (Doctoral thesis), Department of Industrial Engineering, College of Engineering and Informatics, National University of Ireland, Galway, Ireland. Retrieved from <http://hdl.handle.net/10379/3404>
- Sammonds, G.M., Fray, M., & Mansfield, N.J. (2017). Effect of long term driving on driver discomfort and its relationship with seat fidgets and movements (SFM). *Applied ergonomics*, 58, 119-127.
- Smulders, M., Berghman, K., Koenraads, M., Kane, J., Krishna, K., Carter, T., & Schultheis, U. (2016). Comfort and pressure distribution in a human contour shaped aircraft seat (developed with 3D scans of the human body). *WORK*, 54(4), 925-940.
- Van Veen, S., & Vink, P. (2016). Can prior experience influence seating comfort ratings? *ergonomics in design*, 24(2), 16-20.
- Vink, P. (2014). *The sweetness of discomfort: Designing the journey*. (Inaugural address), Delft University of Technology, Delft, The Netherlands. Retrieved from <http://resolver.tudelft.nl/uuid:517db1ea-9e10-4ba7-9bae-f012698eddb3>
- Vink, P., Bazley, C., Kamp, I., & Blok, M. (2012). Possibilities to improve the aircraft interior comfort experience. *Applied ergonomics*, 43(2), 354-359. doi:10.1016/j.apergo.2011.06.011
- Vink, P., & Brauer, K. (2011). *Aircraft Interior Comfort and Design*. Boca Raton, FL, USA: CRC Press. doi:10.1201/b10815
- Vink, P., & Hallbeck, S. (2012). Editorial: Comfort and discomfort studies demonstrate the need for a new model. *Applied ergonomics*, 43(2), 271-276. doi:10.1016/j.apergo.2011.06.001

DESIGN FOR SEATING IN TRANSIT

Part 2 discusses research on activity, pressure distribution and human-contour based designs and design processes. Although it predominantly focusses on aircraft seating, findings can also be applied to the design of other vehicle seats. Chapter 4 discusses the development of a business class seat based on pressure distribution and the human contour, which provides similar (dis)comfort ratings while reducing weight and volume compared to a traditional business class seat. Chapter 5 discusses the same seat, together with two other seat design projects, in order to come to (procedural) recommendations on how to design a seat based on 3D scans of the human body. Chapter 6 investigates how foam spring technology can reduce weight while providing similar/better comfort in a seat pan.

COMFORT AND PRESSURE DISTRIBUTION IN A HUMAN CONTOUR SHAPED AIRCRAFT SEAT (DEVELOPED WITH 3D SCANS OF THE HUMAN BODY)

This chapter has been published as:

Smulders, M., Berghman, K., Koenraads, M., Kane, J. A., Krishna, K., Carter, T. K., & Schultheis, U. (2016). Comfort and pressure distribution in a human contour shaped aircraft seat (developed with 3D scans of the human body). *Work*, 54(4), 925-940.

ABSTRACT

Comfort is one way for the competitive aviation market to differentiate and build customer loyalty. Human contour-based seat design has potential to increase comfort by increasing the contact area between human and seat to lower human-seat interface pressure, and to reduce seat weight and required space volume. This study investigates the influence of human contoured seating on (dis)comfort by means of developing and evaluating a human contour shaped seat shell and cushioning.

The most common activities, the corresponding postures and seat inclination angles were first identified. Imprints of these common postures in a rescue mat were 3D scanned. These scans were used to create an average human contour curve. A prototype seat was designed and built based on this human contour curve, to test its effect on perceived (dis)comfort and pressure distribution.

The resulting human contour-based prototype seat has comfort and discomfort scores comparable to a traditional seat. The prototype seat had a significantly lower average pressure between participants' buttocks and the seat pan than a traditional seat.

This study shows that it is possible to design a seat pan and backrest based on different contours of humans using 3D scan technology. However, translating the 3D scans into a prototype seat also showed that this can only be seen as a first step; additional biomechanical information and calculations are needed to create ergonomic seats. Furthermore, it is not possible to capture all different human shapes and postures and translate these into one human contour shape that fits all activities and all human sizes.

Chapter 5 will give additional recommendations based on this study and other studies.

4.1. Introduction to human contoured seating

After the worldwide COVID-19 pandemic, transport industries are recovering. The air passenger traffic – measured in *revenue passenger-kilometers* (RPK) – increased by 8.8% year-on-year (YoY) in July 2024 (IATA Sustainability & Economics, 2024a). Although the growth is slowing down, it can be seen as a natural development considering that the industry is now surpassing the pre-COVID-19 historical record of 2019 (IATA Sustainability & Economics, 2024b). The growing demand creates opportunities for airlines. By understanding passengers' flight selection behaviour and developing products/services fitting the selection behaviour, airlines can increase passenger revenue (Brauer, 2004).

Brauer (2004) showed that in order of priority, passengers select their flights on point-to-point transport, time, price, and subsequently on aspects such as frequent flyer programs, comfort, past experiences and delays. Comfort is considered a higher priority on long-haul flights. Already in the 1980s, passenger comfort was a key variable for passenger satisfaction and willingness to use the airline again (Richards, 1980). Therefore, passenger comfort might be a way for airlines to differentiate, attract new customers and build customer loyalty.

The comfort of air travel is influenced by several factors. One of the main factors is the seat (Ahmadpour, Lindgaard, Robert, & Pownall, 2014), as it represents the largest contact area during a flight between the passenger and the airplane. Improving this contact area can potentially increase a positive experience of a flight. Several studies about the subject of the contact area and its relation to comfort have been conducted (De Looze, Kuijt-Evers, & Van Dieën, 2003; Zemp, Taylor, & Lorenzetti, 2015) and showed that pressure distribution of the human mass in the seat is one of the best objective methods of getting information about the perceived (dis)comfort of participants. Additionally, Franz et al. (2011) showed a method for developing a contour-based seat in order to increase and subsequently improve the contact area.

The aforementioned studies (De Looze et al., 2003; Franz et al., 2011; Zemp et al., 2015) indicate that a large contact area between the seat and the human decreases the effect of discomfort perception. Therefore, the assumption is that developing an aircraft seat based on the human contour could improve pressure distribution and accordingly increase comfort and decrease discomfort perception. However, these studies are all focussed on car seats. The question is whether a contour-based seat design is also valuable in the field of aircraft seats. Applying the human contour as a base for aircraft seat design is therefore the topic of this study.

Apart from increasing the airline's revenue by attracting more passengers, revenue could also increase by reducing fuel consumption, which has a positive effect on the environment too (Vink, Franz, Kamp, & Zenk, 2012). Making a seat which better fits the human contour could result in the reduction of required seat materials and thereby weight (Franz et al., 2011), which contributes to the reduction of the aircraft's fuel consumption. However, the question is: what is the effect of this light weight human contour-based seat on comfort.

The two main research questions of the study are:

- *Is it possible to design a seat pan and backrest based on the human contour using 3D scan technology?*
- *How does a light weight human contour shaped aircraft seat affect comfort, discomfort and pressure distribution compared to a traditional aircraft seat?*

The research and development of the test seat were focussed on long-haul flights, since long-haul flights are most challenging in terms of comfort.

4.2. Materials and methods

In order to design a seat pan and backrest of an aircraft seat based on the human contour, first the most frequently performed activities in aircraft seats were determined by interviewing three experienced long-haul frequent flyers (age 58–64, flying for both business and leisure). These activities were compared with and confirmed by literature (Gregghi, Rossi, Souza, & Menegon, 2012; Kamp, Kilincsoy, & Vink, 2011). Second, the preferred inclination angles corresponding with the determined activities were established. Third, the human contours in the corresponding inclination angles were captured using 3D scanning. This input was used to develop the shell of the seat, and pressure distribution data completed the cushioning. A prototype was developed with the designed cushioning and shell for testing the effects on comfort, discomfort and pressure distribution. In this study a distinction was made between measuring comfort and discomfort, as Helander and Zhang (1997) showed that these could be different entities when studying a seat.

4.2.1. Inclination for different activities in Business Class aircraft seats

4.2.1.1. Participants

In the first study ten Dutch adults (five male, five female) participated. Care was taken to select participants with a variety of stature and weight (see Table 4.1). All participants frequently flew by plane and two were accustomed to travelling business class.

Table 4.1 | Age and anthropometric measurements of participants (n=10).

		Mean	SD
Male (n=5)	Age [years]	21.0	1.2
	Stature [cm]	184.0	10.6
	Weight [Kg]	74.8	7.9
Female (n=5)	Age [years]	21.8	1.6
	Stature [cm]	170.4	8.2
	Weight [Kg]	62.4	5.3

4.2.1.2. Stimuli

A realistic setting was created by using business class seats placed in a partial airplane cabin with two actors (see Figure 4.1). The actors were seated in the nearby seats to simulate realistic movement and social boundaries. The floor of the business class seats was positioned at a 3° angle to simulate the standard inclination of an airplane during flight at cruising altitude (a.k.a. *angle of attack*). The pitch was set at $60''$ (~ 1.52 metres) (see Figure 4.2), as is standard in business class. Furthermore, participants were provided with hand luggage containing a questionnaire, laptop, magazines, a book, a pen, a sleeping mask and headphones. These objects were used to simulate different activities in a realistic manner. Participants were also provided with food and drinks during the simulated flight by a third actor (the *'flight attendant'*).

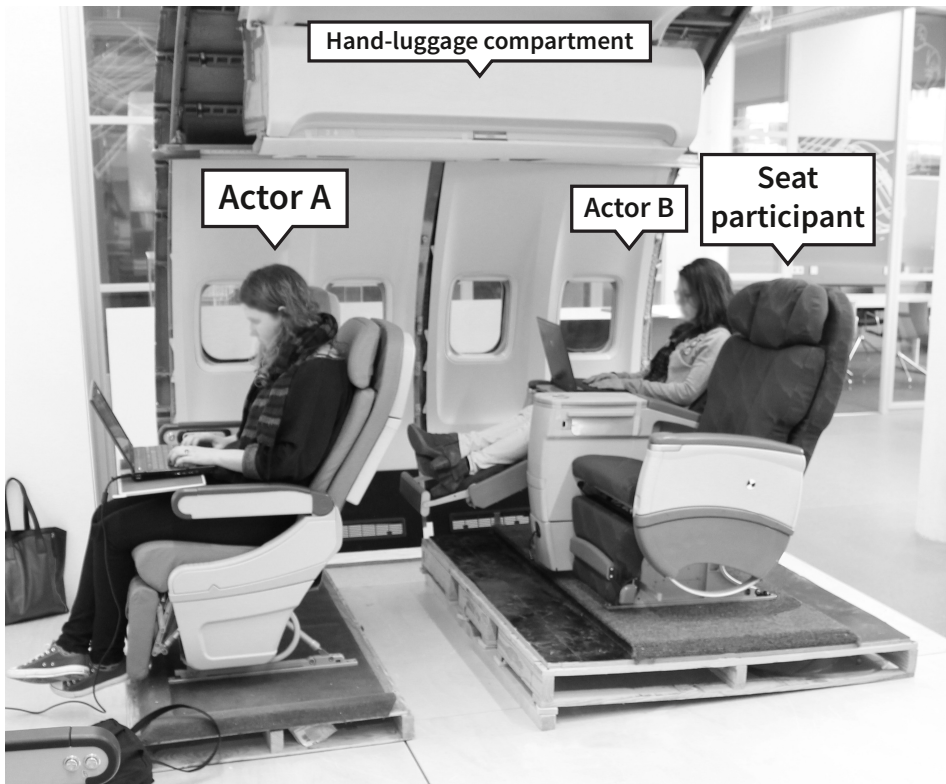


Figure 4.1 | Partial airplane cabin with two actors.



Figure 4.2 | Floor inclination angle and seat pitch.

4.2.1.3. Apparatus

Two cameras were used to capture every posture (Figure 4.3). One camera was fixed and positioned laterally to the passenger; one camera was used to capture interesting details during the test. The lateral pictures were used to trace the position of the backrest, seat pan, leg rest, and determine the angles.

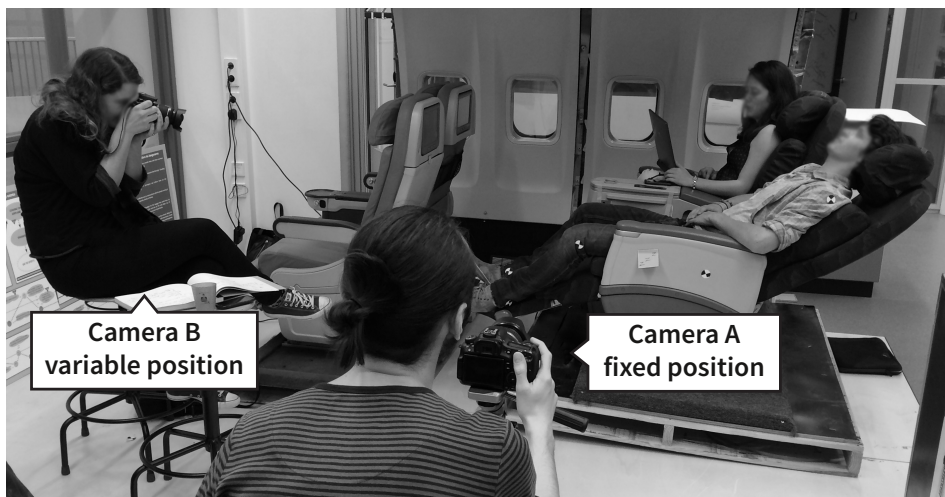


Figure 4.3 | Camera positions.

4.2.1.4. Procedure

Participants were first asked to experience the adaptability of the seat for a couple of minutes. During this activity, the participants were told to pretend to travel by plane and to adjust the seat in the most comfortable position for every activity performed in the seat.

When the participants found a comfortable position and inclination, they mentioned this to the researcher and a picture was taken with both cameras. The participants were asked to confirm the most comfortable position for the activity. When the position was confirmed, the next task was given. This step was repeated for each of the tasks.

The first task was removing hand luggage from the overhead compartment, and filling out a questionnaire about age, gender, stature, weight, and previous flight experiences. Writing served as the first activity in the seat.

Next, drinks and food were offered to provoke an eat/drink posture. While drinking and eating, the participants were asked about their commercial air travel experience and what tasks they performed most during flights. In addition to writing, eating and drinking, and their own mentioned activities, participants were asked to perform the following activities: sleeping, watching In-Flight Entertainment (IFE), listening to music, playing on a smartphone (or tablet), reading a book and working on a laptop.

4.2.1.5. Measures

The pictures taken with the fixed camera were analysed using Adobe Illustrator. The angles of the leg rest, seat pan and backrest were established. These measures were compared with and confirmed by literature (Kilincsoy, Wagner, Bengler, Bubb, & Vink, 2014; Park, Kim, Kim, & Lee, 2000).

4.2.2. 3D scanning the human contour in pre-determined inclinations

4.2.2.1. Participants

In the second study twelve Dutch adults participated (these are different participants than described in §4.2.1.1). Care was taken to select participants with a large variety in stature, weight, and age. Six female and six male participants participated (Table 4.2).

Table 4.2 | Anthropometric measurements of participants (n=12).

		Mean	SD
Male (n=6)	Age [years]	34.3	19.6
	Stature [cm]	183.2	11.3
	Weight [Kg]	90.7	12.7
Female (n=6)	Age [years]	26.8	12.3
	Stature [cm]	167.8	8.8
	Weight [Kg]	65.2	13.2

4.2.2.2. Apparatus

A test seat was built with adjustable leg rest and backrest inclination angles. A rescue mat (further referred to as mat) was positioned on the test seat (Figure 4.4). The mat deformed to the human imprint and held the form after a vacuum was created in the mat using a vacuum cleaner. A 3D laser scanner (*Artec L™* scanner) scanned the human imprint. CAD software (*Artec Studio*) was used to mesh the data. The meshes were processed in *Rhinoceros 3D* to form a 3D representation of the average human contour.



Figure 4.4 | Rescue mat made of a vacuumable sack with Styrofoam balls, in a test seat frame, which allows for backrest and leg rest inclination changes.

4.2.2.3. Procedure

At first participants laid down upon the mat, which was positioned horizontally. Then the leg rest and backrest were inclined by two researchers (Figure 4.5) to a predetermined inclination (Table 4.3), based on the findings of the study described in §4.2.1 (results can be found in §4.3.1).

Table 4.3 | Seat inclinations [degrees] per activity cluster with respect to the vertical (incl. 3° angle of attack; see §4.2.1.2).

	Active	Passive	Sleeping
Backrest	23°	31°	56°
Leg rest	20°	48°	63°
Seat pan	8°	8°	8°



Figure 4.5 | Backrest being reclined with participant.

Participants were asked to sit in a comfortable posture and wiggle their body to get a better imprint. The mat was vacuumed to fixate this imprint. The participant left the seat and the imprint was 3D scanned. After scanning, the air nozzle of the mat was opened and the seat was reclined back into a flat position. Then the mat was massaged to create an even surface again. This process was repeated for each participant, in the three set postures: active, passive and sleeping.

4.2.2.4. Measures

All imprints were individually 3D scanned and meshed. In Rhinoceros 3D a grid with fixed dimensions (seat pan 11x9, backrest 11x9 points) was placed over each mesh. The grid was limited in detail on purpose to avoid minor errors (such as irregular surfaces), – to enhance processing time and to have sufficient detail to get a representative shape. Points on this grid were projected on the mesh, resulting in height maps (Z-coordinate for each XY-coordinate on the grid). The height maps were made for the leg rest, seat pan and backrest individually (see Figure 4.6). To ensure each grid was projected from the same origin, vertical metal pins on the seat (Figure 4.7) were reference points, for alignment of all scans.

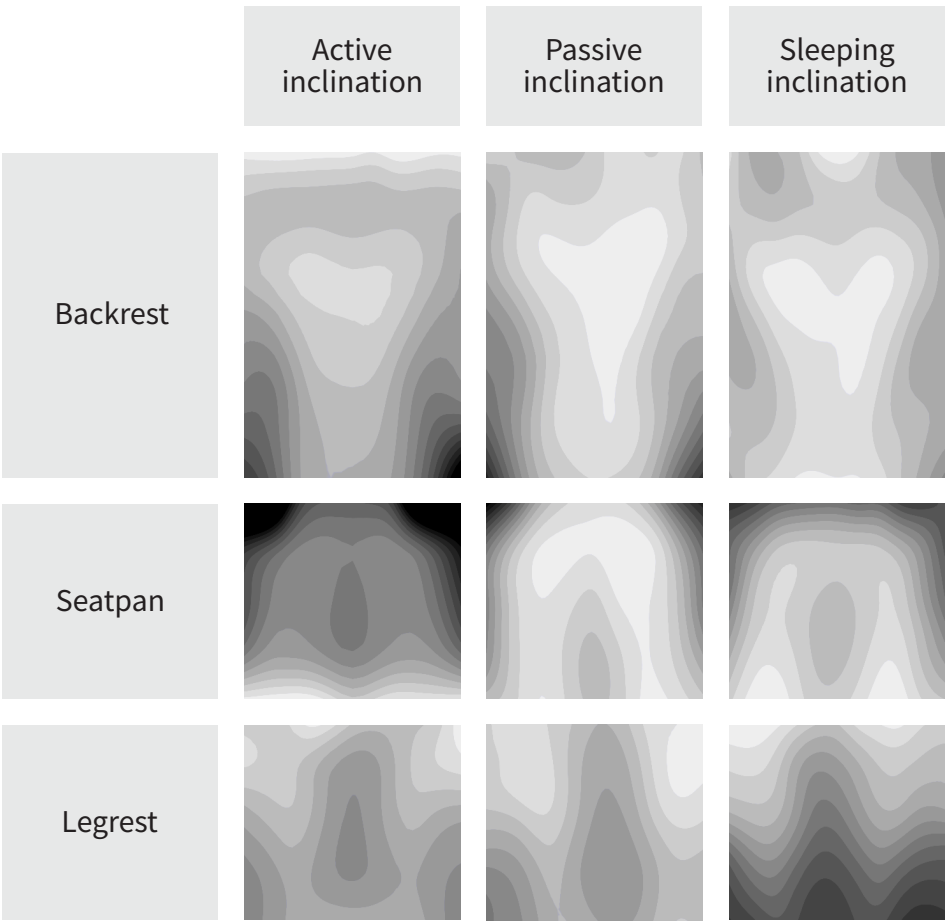


Figure 4.6 | Height map projection of the backrest, seat pan and leg rest of one participant (the lighter, the deeper the imprint).



Figure 4.7 | Reference pins on test seat, covered by socks for safety.

4.2.3. Pressure distribution calculations and testing for cushioning

Since postural change is important for decreasing discomfort during prolonged sitting (Fujimaki & Noro, 2005), it is important that the cushioning does not limit movement, while at the same time providing a large contact area. Thick, soft cushioning for example will have a large contact area, but it impedes movement.

Since the seat's shell (in this design) is a single curved 2D shape (see §4.2.4), the 3D human contour is achieved by varying the firmness of the cushioning. The thickness of the cushioning was set to 30mm, for the purpose of weight and space reduction. The new cushioning is relatively thin compared to the traditional cushioning of 85-139mm. The firmness needed for the cushioning to create the average human 3D curve was calculated with the help of the ideal pressure distribution (Zenk, Franz, Bubb, & Vink, 2012) and validated using a theory for calculating cushion indentation (Goossens, 1994). The ideal pressure distribution avoids pressure peaks on softer tissues of the body since this is healthier (Goossens, 1994). For calculation purposes, the unit IFD was used. IFD represents the Indentation Force Deflection, which is the force [Newtons] needed to indent the material 25% of its original thickness.

The input for calculating the IFD is the force [Newtons] on the cushioning and the desired indentation of the cushioning. The force was calculated (Chow & Odell, 1978) based on the pressure distribution as represented by Franz et al. (2011) (Figure 4.8). The pressure distribution was translated into the maximum pressure and subsequently into maximum load per body area as sectioned in the pressure distribution figure. These sections were chosen to simplify the pressure distribution in 3 equally sized areas: the

buttocks, the thighs and the knee cavities. The seat pan and backrest were divided into a grid and afterwards the maximum force per grid square was calculated. The desired indentation per grid square was derived from the average human 3D shape as a result from §4.2.2. The IFD was calculated with the maximum force per grid square and the desired indentation per grid square. The data was checked using the percentage of the body mass from different body parts (Vink & Brauer, 2011). The different masses per body area were translated into the resulting force per grid square to check the calculations.

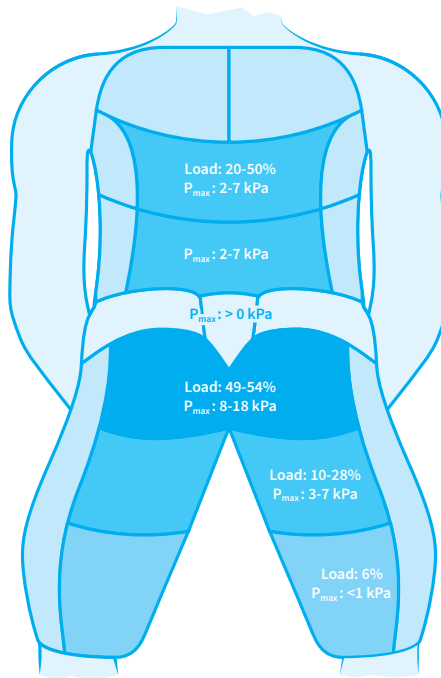


Figure 4.8 | Pressure distribution as described by Raphael Zenk (2008) based on Mergl (2006). Note that the values in the leg pertain to both legs together.

Based on the calculated firmness, cushioning was prototyped by using different firmness variants of AMES DISTO® Spacer Fabric (Figure 4.9). The comfort of the cushioning on the shell was optimised using a trial-and-error validation test. Twelve participants sat on the seat for five minutes (Figure 4.10) and subsequently completed a Local Postural Discomfort (LPD) form, indicating discomfort per body area. The form provided an indication whether the cushioning per body area felt too soft, too firm, or just right (Figure 4.11). The cushioning was adjusted and the test repeated until the participants rated the cushioning as satisfactory.

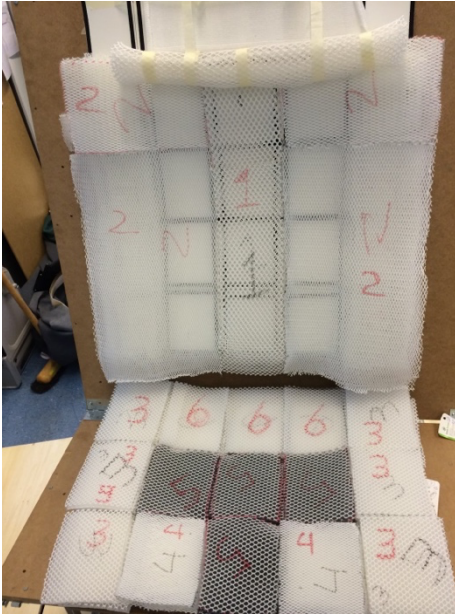


Figure 4.9 | Prototyped cushioning made of knitted Spacer Fabric.



Figure 4.10 | Trial and error test for finding a comfortable cushioning firmness distribution.

Name: _____

Gender: _____

Weight: _____

Height: _____

Figure 4.11 | Local Postural Discomfort (LPD) like form for the back, buttocks and upperlegs, asking to rate each zone as *Too soft*, or *Perfect*, or *Too hard*.

4.2.4. Prototyping business aircraft seat based on the human contour

The 3D representation of the average human contour was used to develop the business class aircraft seat. The seat consisted of a hard shell, padded with cushioning. To develop the shell, the average 3D surface was simplified into a 2D line. The line represented the (average) curve of the spline, which was also the deepest part of the surface. The 2D line was translated into a shell, which forms the structural shape of the seat. Aluminium sheets were bent into the shape to form a mould. A sheet of TenCate Cetex® TC925 FST Polycarbonate Thermoplastic Resin System was then thermoformed onto the aluminium mould. The TenCate Cetex® sheets were considered suitable since the sheets are currently used in aircraft interiors for its properties related to flame retardant qualities, density and strength. Because the cushioning was firmer on the lateral sides of the seat, a 3D human contour was recreated. The cushion parts with different firmness were sewn together as one seat pan and one backrest cushion. The cushioning was mounted onto the hard shell and covered with fabric. During the study as described in §4.2.5, the shell was supported by a wooden frame. In the final prototype the common aluminium frame of traditional business class seats was replaced by a new designed carbon fibre frame with CNC milled foam core, to reduce the weight of the seat.

The reduction in weight of this new seat (compared with the traditional one) was estimated at 10.25kg per seat, thanks to the use of lower density and less materials (−9.9kg), lighter cushioning (−1.1kg) and the change to thicker breathing fabric (+0.75kg). However, extra weight can be expected since the prototype does not meet the strict aviation safety and crash regulations.

4.2.5. Comfort and discomfort effects of the prototype and traditional seat

4.2.5.1. Participants

Twenty people participated in the third study (these are different participants than described in §4.2.1.1 and §4.2.2.1). Care was taken to select participants with a variety in stature, weight, and age. Ten female and ten male participants participated (Table 4.4).

Table 4.4 | Anthropometric measurements of participants (n=20).

		Mean	SD
Male (n=10)	Age [years]	31.6	21.2
	Stature [cm]	182.4	10.9
	Weight [Kg]	83.6	17.0
Female (n=10)	Age [years]	31.6	13.2
	Stature [cm]	172.7	8.6
	Weight [Kg]	78.0	14.5

4.2.5.2. Apparatus

A prototype seat was built with the 2D curved shell and the cushioning, as described in §4.2.4. The prototype seat was positioned in an existing framework of two business class seats with one seat removed. As a result, the test setting consisted of an existing business class seat and the prototype seat. The seats were covered with a white sheet to prevent prejudice by appearance. Both of the seats had a 20° inclined backrest, an 8° inclined seat pan, a 20° inclined leg rest and a footrest perpendicular to the leg rest (all including a 3° inflight inclination). The inclination resembled the active position as determined in §4.2.1. This posture was selected since it causes the highest pressure points on the seat and was therefore deemed the most interesting to investigate. A wooden wall simulated the pitch size of 1.5-meter which is common for long-haul business class and contained two 20" screens as IFE (Figure 4.12). Two small tables, headphones, food and drinks were provided. Furthermore, human measurements were taken using an anthropometer, an adjustable measuring seat and a digital scale.



Figure 4.12 | Experimental setup

4.2.5.3. Procedure

Prior to the study, participants received a letter with instructions not to wear clothing with solid components on their buttocks and back (e.g. buttons, buckles and zippers) to prevent influencing perceived comfort, discomfort and measured pressure, as these items can cause peak pressures.

Participants were seated in pairs (to prevent order effects, as both groups of participants of equal size follow an opposite order) and experienced each seat for 90 minutes. Each pair of participants sat in the existing seat (seat A) and the prototype seat

(seat B). After 90 minutes the participants took a break. The break was used to conduct the research described in §4.2.6 and take anthropometric measurements of the participants, such as weight, stature and hip width. Furthermore, the participants had a chance to walk and use the toilet before switching seats for the other 90 minutes of sitting. The participants were asked to choose one activity to conduct during the entire experiment: working on a laptop, reading or watching IFE. Only one activity was permitted as large postural change would influence perceived comfort and discomfort too much over time, making a time dependent comparison impossible. Every 15 minutes the participants described their overall comfort on a 0–5 Likert scale and every 30 minutes the participants completed a LPD form (see Figure 4.13). Participants were requested not to leave the seat during the 90 minutes. Drinks and snacks were offered.

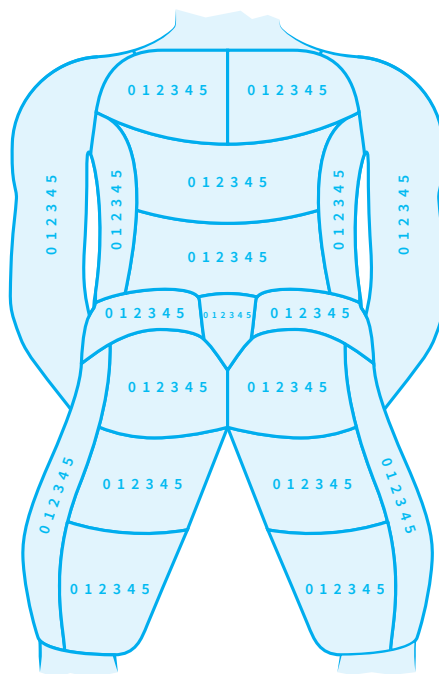


Figure 4.13 | LPD form for the back, buttocks and upperlegs (based on Mergl (2006), derived from Van der Grinten and Smitt (1992) and Corlett and Bishop (1976)).

4.2.5.4. Measures

All comfort and discomfort ratings per seat were compared over time and per seat using Microsoft Excel and IBM SPSS. Because comfort values are not normally distributed, the Wilcoxon Signed-Rank Test was used, to look for differences between the prototype and traditional seat. The significant differences between total comfort and discomfort score were calculated ($p < 0.05$), and also between regions in the body (buttocks and lower back).

4.2.6. Pressure distribution effects of the prototype and traditional seat

4.2.6.1. Participants

Pressure distribution of the prototype and traditional seat was recorded with the same participants from §4.2.5.1.

4.2.6.2. Apparatus

The same test set up with two seats as mentioned in §4.2.5.2 was used. A mFLEX 4.0 UT4010-7000 pressure mat (sensor matrix of 32x16) and a laptop with FSA software were used to measure the pressure distribution in both the existing and the prototype seat.

4.2.6.3. Procedure

During the break described in §4.2.5.3, the pressure mat was subsequently placed in both the test seat and the existing seat, covering the seating area from the knee cavities up to and including the lower back. The focus was on measuring the sitting area, since it, has the most influence on comfort. The participants sat in the seat on the mat for 5 minutes for posture settlement (Kyung & Nussbaum, 2008). Then the pressure distribution was recorded.

4.2.6.4. Measures

With the FSA software the pressure in kilopascals (kPa) per cell was determined. Pressure plots were saved as a reference to check the calculated pressure distribution, to help determine the position of body parts and to detect inaccuracies in the measurement (e.g. folds and pressure points caused by other body parts than buttocks and back).

Measurements of the average pressure were calculated for the seat pan and the back for both seats, by summing the measured pressures and dividing the total pressure by the number of cells that were activated. Additionally, the contact areas in the seat pan and backrest were calculated by counting the number of cells that were activated. A t-test for paired comparison was used to check on significant differences between the prototype and traditional seat ($p < 0.05$).

4.3. Results

4.3.1. Inclination for different activities in Business Class aircraft seats

The results of the mean angles and standard deviation (SD) of the backrest and leg rest inclination of the experiment described in §4.2.1 are shown in Table 4.5.

Table 4.5 | Backrest and leg rest angles [degrees] (n=10, except 'Listen to music') with respect to the vertical (incl. 3° angle of attack; see §4.2.1.2).

	Backrest angle		Leg rest angle	
	Mean	SD	Mean	SD
Write	20.5°	±5.5°	28.5°	±19.1°
Eat & drink	20.4°	±5.0°	37.9°	±22.1°
Sleep	55.5°	±0.6°	63.1°	±2.3°
Watch IFE	31.7°	±5.6°	50.0°	±20.2°
Listen to music (n=6) ¹	36.3°	±11.3°	51.0°	±14.7°
Play/work on mobile phone/tablet	31.3°	±7.6°	43.4°	±20.3°
Read book	30.2°	±6.4°	49.0°	±14.9°
Work on laptop	27.5°	±7.6°	42.1°	±19.2°

¹ Four participants did not performed this activity, as a mistake was made in the protocol execution.

Plotting the results graphically (see Figure 4.14) showed that the inclinations of different activities can be clustered into roughly three positions: active, passive and sleeping. Active activities used a relative upright backrest inclination and downward leg rest inclination. More 'passive' activities, such as watching IFE, had a relatively downward backrest inclination and upward leg rest inclination. Sleeping had an 'as flat as possible' inclination.

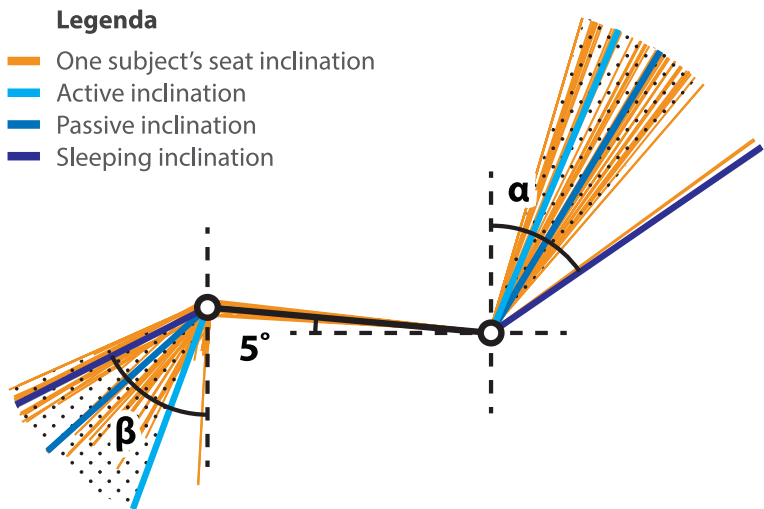


Figure 4.14 | Plotted inclination angles (excl. 3° angle of attack).

When combining all measures, three main business class inclinations were determined (see Table 4.6). These three inclination clusters were used in the ‘3D scanning the human contour in pre-determined inclinations’ study, as described in §4.2.2. Comparing the results with literature (Helander & Zhang, 1997; Kilincsoy et al., 2014) showed similarities. Kilincsoy et al. (2014) described an active posture with a 105° trunk thigh angle, confirming this study’s active inclination angle. Park et al. (2000) describe a 117° trunk thigh angle, similar to this study’s passive inclination angle.

Table 4.6 | Seat inclinations [degrees] (mean and SD) per activity cluster with respect to the vertical (incl. 3° angle of attack; see §4.2.1.2).

	Active		Passive		Sleeping	
	Mean	SD	Mean	SD	Mean	SD
Backrest	22.8°	±6.8°	31.0°	±7.7°	55.5°	±0.6°
Leg rest	20.3°	±20.3°	48.1°	±17.5°	63.1°	±2.3°
Seat pan	8°		8°		8°	

4.3.2. 3D scanning the human contour in pre-determined inclinations

The results of the measures (the grid projections) were positioned in the same plane to determine an average of all scans. For each cluster of points on each XY coordinate a mean could be determined by averaging the Z-coordinates of the grids.

The result was an averaged point grid, converted into a non-uniform rational B-spline (NURBS) surface. The surface was a smooth 3D representation of the average human contour of the scanned participants in all the three sitting positions (Figure 4.15). These surfaces were used in §4.2.4.

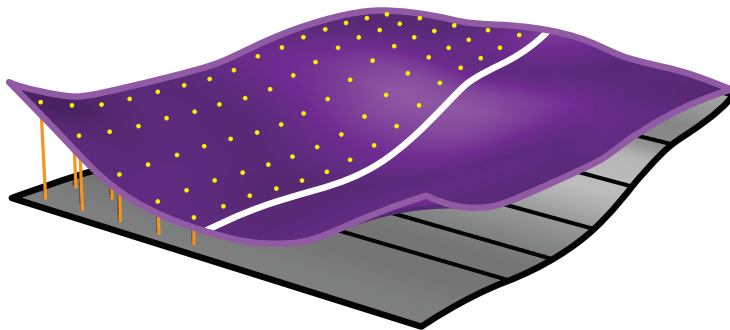


Figure 4.15 | Average seat pan double curved surface (purple surface) based on the average point grid of the seat pan (yellow dots on purple surface). As described in §4.2.3, this average double curved surface was used to design the cushioning firmness for different areas, allowing for supporting the human curvature through foam indentation. The white line in the middle is the centre curvature/spline. As described in §4.2.4, this which was used to create the hard-shell design (shown in gray).

4.3.3. Pressure distribution calculations and testing

The calculations for the ideal pressure distribution cushioning developed for the human contour-based shape resulted in IFD values. The IFD values per body region, divided in blocks of 50×50mm, can be found in Table 4.7 and Table 4.8. The IFD values and the recorded average human contour shape formed the base for the trial-and-error testing. By putting pieces of cushioning with different firmness's on top of the contoured shell, an attempt was made to arrive as close as possible to the calculated IFD values. This process resulted in the final cushioning design made of separate pieces of different thicknesses and firmnesses (see Figure 4.16), which were sewn together into one layered cushion. To limit the influence of the seams on the cushion properties, but at the same time be small enough to create the ideal pressure distribution-based cushioning, block sizes of 140×165mm were used.

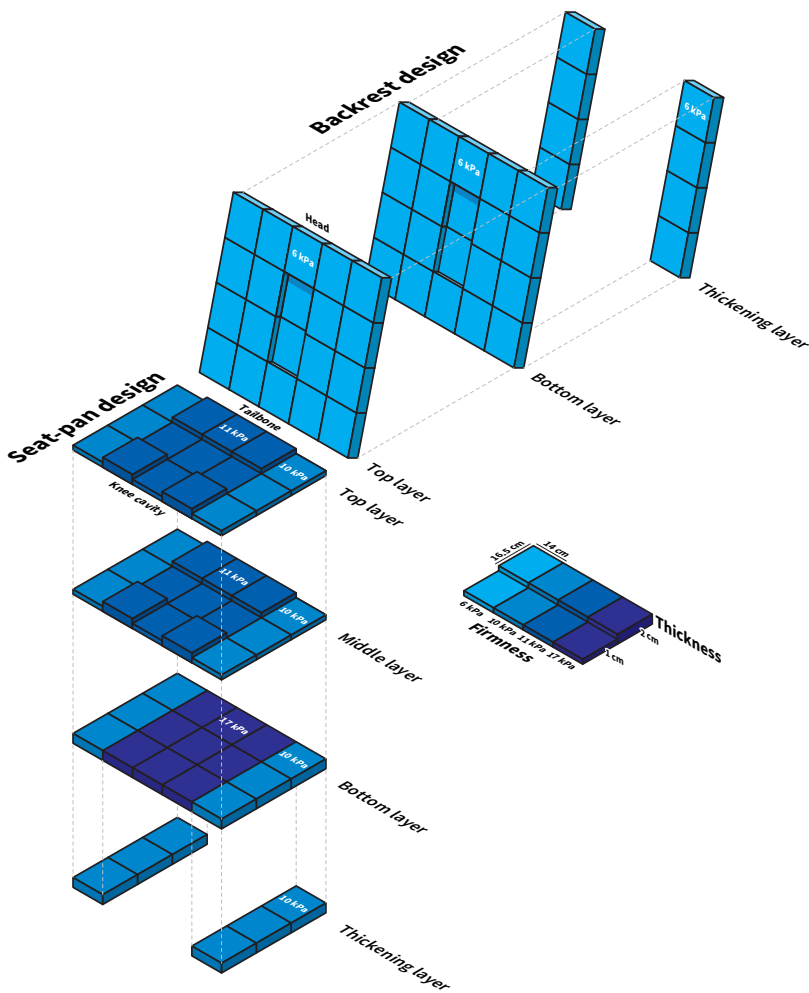


Figure 4.16 | Cushioning designs for the seat pan and backrest with different firmness and layer thickness sections.

Table 4.7 | Backrest IFD values [Newton] calculated for each 50x50mm square. Lower IFD values correspond with less firmness; higher IFD values with greater firmness.

Head										
Backrest	3.33	1.37	-1.29	-2.73	-3.06	-3.06	-2.73	-1.29	1.37	3.33
	0.82	-0.82	-2.34	-3.02	-3.08	-3.08	-3.02	-2.34	-0.82	0.82
	-0.61	-2.06	-2.96	-3.14	-2.98	-2.98	-3.14	-2.96	-2.06	-0.61
	-0.40	-0.88	-1.11	-1.09	-0.97	-0.97	-1.09	-1.11	-0.88	-0.40
	-0.48	-0.95	-1.12	-1.04	-0.88	-0.88	-1.04	-1.12	-0.95	-0.48
	-0.51	-0.96	-1.11	-0.99	-0.80	-0.80	-0.99	-1.11	-0.96	-0.51
	-0.08	-0.13	-0.16	-0.14	-0.11	-0.11	-0.14	-0.16	-0.13	-0.08
	-0.09	-0.13	-0.15	-0.14	-0.11	-0.11	-0.14	-0.15	-0.13	-0.09
	-0.11	-0.13	-0.15	-0.14	-0.12	-0.12	-0.14	-0.15	-0.13	-0.11
Tailbone										

Table 4.8 | Seat pan IFD values [Newton] calculated for each 50x50mm square. Lower IFD values correspond with less firmness; higher IFD values with greater firmness.

Tailbone										
Seat pan	0.42	0.13	-0.33	-0.64	-0.72	-0.72	-0.64	-0.33	0.13	0.42
	0.58	0.28	-0.22	-0.58	-0.71	-0.71	-0.58	-0.22	0.28	0.58
	0.68	0.39	-0.12	-0.53	-0.70	-0.70	-0.53	-0.12	0.39	0.68
	0.42	0.25	-0.05	-0.31	-0.42	-0.42	-0.31	-0.05	0.25	0.42
	0.39	0.22	-0.07	-0.32	-0.42	-0.42	-0.32	-0.07	0.22	0.39
	0.38	0.20	-0.10	-0.34	-0.43	-0.43	-0.34	-0.10	0.20	0.38
	0.18	0.08	-0.04	-0.12	-0.15	-0.15	-0.12	-0.04	0.08	0.18
	0.25	0.11	-0.03	-0.12	-0.15	-0.15	-0.12	-0.03	0.11	0.25
Knee cavity										

4.3.4. Prototyping business aircraft seat based on the human contour

The shape of the seat was based on a hard shell and cushioning design. All previously stated findings are combined in the prototype.

4.3.5. Comfort and discomfort effects of the prototype and traditional seat

The goal of this study was to find out if there was a difference in comfort and discomfort between the existing (seat A) and the prototype (seat B) seat.

Regarding the discomfort scores given on the LPD forms, there was no significant difference in the overall-, lower back- and buttocks discomfort scores between seat A and seat B (see Table 4.9). However, there are overall, lower back and buttock discomfort differences between time intervals within the same seat (see Table 4.10): predominantly between 30-60 min. and 30-90 min. intervals.

The differences in comfort in seat A and seat B are shown in Table 4.11. There was no significant difference in comfort between seat A or B at any time. The comfort in seat A decreased significantly over time (see Table 4.12) in the period from 45–60 minutes in the seat ($p=.020$) and during the overall period from 15–90 minutes in the seat ($p = .003$). The comfort in seat B decreased significantly over time in the period from 30–45 minutes ($p = .014$) and during the overall period from 15–90 minutes in the seat ($p = .012$).

Table 4.9 | Discomfort scores (mean and SD) of seats A and B, and the difference (Wilcoxon signed rank test) of discomfort between seats A and B (n=20).

	Time	30 min		60 min		90 min	
	Seat	A	B	A	B	A	B
Overall discomfort	Mean	3.9	6.2	8.1	6.6	7.9	9.7
	SD	2.3	4.7	6.3	4.4	8.4	5.8
	p-value	.063		.532		.152	
Lower back discomfort	Mean	1.2	1.9	3.2	3.4	3.2	4.4
	SD	1.0	1.6	2.8	3.9	2.8	3.3
	p-value	.056		.833		.274	
Buttocks discomfort	Mean	1.2	1.8	3.3	2.0	3.6	4.1
	SD	1.9	3.1	5.3	2.2	5.8	5.3
	p-value	.270		.489		.120	

Table 4.10 | Wilcoxon signed rank test p-value of overall, lower back and buttock discomfort difference between time intervals within the same seat (n=20).

Compared time intervals		Seat A p-value	Seat B p-value
Overall discomfort	30-60 min.	0.001*	0.161
	60-90 min.	0.616	0.060
	30-90 min.	0.015*	0.001*
Lower back discomfort	30-60 min.	0.002*	0.047*
	60-90 min.	0.649	0.310
	30-90 min.	0.003*	0.007*
Buttocks discomfort	30-60 min.	0.005*	0.384
	60-90 min.	0.838	0.007*
	30-90 min.	0.031*	0.004*

Table 4.11 | Comfort scores (mean and SD) of seats A and B, and Wilcoxon signed rank test p-value of discomfort difference between seats A and B (n=20).

Time	15 min		30 min		45 min		60 min		75 min		90 min	
Seat	A	B	A	B	A	B	A	B	A	B	A	B
Mean	4.3	4.0	4.2	3.9	4.0	3.6	3.7	3.5	3.6	3.4	3.5	3.5
SD	0.6	0.8	0.6	0.7	0.5	0.9	0.7	0.8	0.7	0.8	0.8	0.9
p-value	.132		.212		.059		.490		.273		.776	

Table 4.12 | Difference in comfort (p-value) at different times within same seat (n= 20)

Compared time intervals	Seat A p-value	Seat B p-value
15-30 min.	.414	.414
30-45 min.	.083	.014*
45-60 min.	.020*	.414
60-75 min.	.705	.180
75-90 min.	.317	.317
15-90 min.	.003*	.012*

4.3.6. Pressure distribution effects of the prototype and traditional seat

The mean pressure of the seat pan of seat A (traditional seat) mean $\pm$ SD was 6.0 $\pm$ 1.4 [kPa/cell] and of seat B (prototype seat) mean $\pm$ SD was 4.8 $\pm$ 1.5 [kPa/cell], which was significantly different ($p<0.001$). This means there was a lower average pressure in the prototype seat's seat pan. The mean pressure of the lower backrest of seat A was mean $\pm$ SD 1.2 $\pm$ 0.4 [kPa/cell] and of seat B mean $\pm$ SD 2.5 $\pm$ 0.8 [kPa/cell], which was significantly different ($p<0.001$). This means there was higher average pressure in the prototype seat's backrest. The number of recorded contacts of the seat pan for seat A was 144.3 $\pm$ 23.5 [cells] and for seat B 123.0 $\pm$ 18.5 [cells], which was also a significant difference ($p<0.001$). The number of recorded contacts of the backrest for seat A was 73.8 $\pm$ 25.9 [cells] and for seat B 50.6 $\pm$ 14.4 [cells], which was also a significant difference ($p<0.001$). This means the contact area in seat A was larger than in seat B for both the seat pan and the backrest.

4.4. Discussion

4.4.1. Inclination for different activities in Business Class aircraft seats

During the inclination study, it was noted that participants did not always change their inclination when conducting another activity. As participants were asked to move from one activity to another, without the request to adjust the seat to the initial inclination first, the inclination of one activity could influence the inclination of the next activity as described by Helander, Little, and Drury (2000). The order effect on the resulting inclination preferences was not further investigated, but it could have disturbed the results. Participants may judge their current inclination as sufficiently comfortable to conduct their new activity and therefore will not feel the urge to adjust their inclination for a better one. For further research, it is therefore recommended to incline the test seat back into a standard position after each performed activity or to follow a random order.

4.4.2. 3D scanning the human contour in pre-determined inclinations

The first research question considered the link between 3D scanned human contours and defining the shape of the seat. This study showed that it is possible to use the form as a base. However, due to the variation of body anthropometrics a creative step was needed. By using a grid and condensing the data, a 2D form could be defined and by adding variation in foam firmness a translation to a seat could be made.

As stated in §4.2.2.4 vertical metal pins on the seat (Figure 4.7) were used as reference points, to align all 3D scans. However, this was not ideal, because participants never sat in the exact centre of the rescue mat. A better method would be to use a software algorithm to superimpose the scans into an average curve, as Hiemstra-van Mastriht (2015) did in the YZ-plane.

Franz et al. (2011) used a similar technique. They arranged the scanning data in a position, approaching the scatter plots of the scans as close as possible to each other, using a best-fit algorithm. They also used a creative solution to combine the scans by prioritizing areas which are most important for comfort.

Apparently, a one-to-one translation from scan to seat is not possible for groups of users. A one-to-one translation often results in a more or less even pressure on the body, while some parts of the body are more sensitive to pressure and others can handle more pressure. Franz et al. (2011) and Smulders, van Dijk, Song, Vink, and Huysmans (2023) (see Chapter 10) showed that in the neck less pressure was acceptable than on the back of the head. Zenk et al. (2012) showed that more pressure was preferred on the buttocks than under the front of the legs. A comfortable posture in the rescue mat does not guarantee an ergonomically correct posture. Additional creative steps and testing are therefore recommended to encourage people to adopt a better posture, which will lead to more comfort in the long term. Therefore, biomechanical models and mathematical steps need to be taken in order to develop an ergonomic seat.

Another factor which makes the interpretation complex is that different activities are performed in the same seat (Gregghi et al., 2012). Scans of different persons performing different activities should be combined. This study clearly shows that the angles of backrest and leg rest differ per activity, which was also described previously by Groenesteijn et al. (2014). This means that a 3D scan is helpful for the design, but a creative step to translate it into a product is still needed (see Chapter 5).

The approach used in this study is effective, but Franz et al. (2011) show another possibility of measurement: they suggested using inflatable cushioning, which is made of inflatable compartments. By pumping air in or out, the firmness per region can be adjusted, which allows the seat to match every individual's contour.

Lastly it is important to note that the resulting average curve of the human contour in this study is based on Dutch participants only, who are relatively tall compared to an international target population (Molenbroek et al., 1984-2020). It is therefore recommended to take the target population (e.g. international, children) into account when selecting participants for gaining a representative average or ideal curve.

4.4.3. Pressure distribution calculations and testing

By adding the cushioning with different firmnesses to the shell, the 2D shaped shell was translated to the 3D human contour-based shape. Postural differences between different people were addressed. As the cushioning on the sides of the seat is more firm, larger, and heavier people will cause the cushioning on the sides of the seat to indent as well. Smaller and lighter people will not cause the cushioning on the sides of the seat to indent. Therefore, the seat supports different contours for larger and smaller people.

Whilst calculating the firmness of the cushioning, some assumptions were made. First, the ideal pressure distribution as described by Mergl (2006) and Zenk (2008) was projected onto the seat. As the exact measurements of the pressure distribution depend on the anthropometrics of the participant, the pressure distribution was simplified in three equally sized areas: the buttocks, the thighs and the knee cavities. Secondly, the seat pan and backrest were divided into a 50×50mm grid to calculate the different forces. The size of the grid may have influenced the IFD values. A smaller grid would have given more exact values, although the ideal pressure distribution as described by Mergl (2006) and Zenk (2008) was not detailed enough to make more precise calculations. Additionally, the used cushioning did not allow for smaller squares.

4.4.4. Prototyping business aircraft seat based on the human contour

The prototype used during the study as described in §4.2.5 was supported by a wooden frame, which was not adjustable, and the footrest was not attached to the seat. Therefore, the prototype was different from the traditional seat, as the traditional seat had an adjustable footrest attached to the leg rest. Although one participant assumed the traditional seat was the newly developed seat, it can be questioned whether participants were prejudiced by the test setup and the difference of the two seats was visible. As a recommendation for future research, both seats should look the same in all aspects to prevent participants' visual interpretation having an influence on their perceived comfort and discomfort.

4.4.5. Comfort and discomfort effects of the prototype and traditional seat

The study to answer the second research question concerning the difference in comfort and discomfort between both seats showed no significant differences. Interpreting this result might lead to the conclusion that reducing the weight is possible without large effects on comfort.

The cushioning of the prototype was 30mm thick, and the cushioning of the traditional seat was to 85-139mm thick in the seat pan and 133mm thick in the backrest. Thus, the contour-based seat was 65-78% thinner in the seat pan and 77% thinner in the backrest compared to the traditional seat. The thickness of the backrest has a direct effect on the pitch length; the new backrest design is 83mm thinner. Valuable space was saved whilst the same level of comfort was obtained. This has also been described for car seats (Franz et al., 2011; Vink et al., 2012).

Although there was no significant difference in discomfort ratings between the seats throughout the experiments, discomfort was close to (but not) significantly higher in the prototype seat at the beginning of the test (after 30 minutes). Ahmadpour et al. (2014) showed that the first 30 minutes of the flight are crucial since it has major influence on the experience of the total flight. It is therefore recommended to further optimise the seat form or cushioning, to improve the experience in the first 30 minutes.

4.4.6. Pressure distribution effects of the prototype and traditional seat

The pressure distribution showed that the pressure was better distributed in the seat pan, but less in the back in the prototype seat (see §4.3.6). Literature shows that a lower average pressure is accompanied by less discomfort (e.g. Noro, Naruse, Lueder, Nao-i, and Kozawa (2012)). However, this is not affirmed in this study, because there was no significant difference in discomfort between the prototype and traditional seat. The results show that the contact area in the traditional seat is larger than in the prototype seat. This was due to the soft, thick cushioning, which however impaired movement.

The higher pressure in the backrest of the prototype seat may have caused the discomfort in the lower back, compared with the traditional seat. Further research and redesign of the backrest are recommended to improve pressure distribution.

4.5. Conclusion

This study showed that it is possible to design a seat pan and backrest based on the human contour using 3D scan technology. However, a creative and/or mathematical process is needed to translate the scan data into curvature and cushioning designs. It is not possible to capture all different human shapes and postures and translate these to one average human contour shape that fits all activities and all humans; design choices and compromises are necessary.

The light weight human contour shaped business class aircraft seat did not affect the comfort, discomfort and pressure distribution when compared to a traditional business class aircraft seat. However, small differences could be distinguished especially in the lower back. Furthermore, the mean pressure between the human and seat pan was lower in the new seat compared to the traditional seat. Due to discomfort and higher than average pressure, it is advised to adjust the lower part of the backrest and further study the effects.

This study shows that a light weight and thin human contour-based seat has the potential to achieve similar comfort and discomfort ratings as a traditional heavy and bulky business class seat.

4.6. Acknowledgements

Thank you to all my team members for the amazing collaboration and tons of fun (even when we had to work till late through the night to meet our deadlines) in this research and design project; ir. M. Koenraads, ir. J.A. Kane, ir. K. Krishna, ir. T.K. Carter, with a special thanks to ir. K. Berghman, with whom I did the majority of this research.

I also want to thank ir. A. Vogel, ir. J.A. Stewart, ir. A.J. Weiss, ir. L.J. Lam, ir. A.L.E. de Vries and ir. S.H.F. van Gils for collaborating with 3D scanning the human contour and processing the results. Staff of the Delft University of Technology, for their help, advice and/or guidance in this project: prof.dr. P. Vink, B.J. Naagen, ir. R. van der Horst, prof.dr.ir. R.H.M. Goossens and dr. H.F. Broekhuizen. For facilitating prototyping: Delft Aerospace Structures and Materials Laboratory of the faculty Aerospace Engineering of the Delft University of Technology, Model Making and Machine Lab (PMB) of the faculty Industrial Design Engineering of the Delft University of Technology, and I.J. Berghman of Batist Westland.

Special thanks to dr. U. Schultheis, ir. F. Lee, ir. S. Does and Safran Seats US (formerly Zodiac Seats US LLC), for supporting this research and design project. H. Albers and Royal TenCate N.V. for supplying fiber materials and J. Berning and Ames Europe B.V. for supplying knitted spacer fabric. R. Könemann and TNO (Netherlands Organisation for Applied Scientific Research) for lending the rescue mat. And lastly, thank you to all the participants who took part in this study.

4.7. References

- Ahmadpour, N., Lindgaard, G., Robert, J.-M., & Pownall, B. (2014). The thematic structure of passenger comfort experience and its relationship to the context features in the aircraft cabin. *Ergonomics*, 57(6), 801-815. doi:10.1080/00140139.2014.899632
- Brauer, K. (2004). *Convenience, comfort, and costs*. Presentation at the Aircraft Interior EXPO, Hamburg, Germany.
- Chow, W., & Odell, E. (1978). Deformations and stresses in soft body tissues of a sitting person. *Journal of Biomechanical Engineering*, 100, 79-87.
- Corlett, E.N., & Bishop, R. (1976). A technique for assessing postural discomfort. *Ergonomics*, 19(2), 175-182. doi:10.1080/00140137608931530
- De Looze, M.P., Kuijt-Evers, L.F.M., & Van Dieën, J.H.L. (2003). Sitting comfort and discomfort and the relationships with objective measures. *Ergonomics*, 46(10), 985-997.
- Franz, M., Kamp, I., Durt, A., Kilincsoy, Ü., Bubbs, H., & Vink, P. (2011). A light weight car seat shaped by human body contour. *International Journal of Human Factors Modelling and Simulation*, 2(4), 314-326. doi:10.1504/ijhfm.2011.045002
- Fujimaki, G., & Noro, K. (2005). Sitting comfort of office chair design. Paper presented at the Proceedings of the 11th International Conference on Human-Computer Interaction, Las Vegas, Nevada, USA.
- Goossens, R.H.M. (1994). Biomechanics of body support: A study of load distribution, shear, decubitus risk and form of the spine. (Doctoral dissertation), Erasmus University, Rotterdam, the Netherlands.
- Gregghi, F., Rossi, N., Souza, G., & Menegon, L. (2012). Contributions from the activity analysis to the products development project: case study based on a project of innovation and comfort in aircraft's cabins. *WORK*, 41(Supplement 1), 55-60. doi:doi.org/10.3233/WOR-2012-0135-55
- Groenesteijn, L., Hiemstra-van Mastrigt, S., Gallais, C., Blok, M., Kuijt-Evers, L., & Vink, P. (2014). Activities, postures and comfort perception of train passengers as input for train seat design. *Ergonomics*, 57(8), 1154-1165.
- Helander, M.G., Little, S.E., & Drury, C.G. (2000). Adaptation and sensitivity to postural change in sitting. *Human factors*, 42(4), 617-629.
- Helander, M.G., & Zhang, L. (1997). Field studies of comfort and discomfort in sitting. *Ergonomics*, 40(9), 895-915. doi:10.1080/001401397187739
- Hiemstra-van Mastrigt, S. (2015). Comfortable passenger seats: Recommendations for design and research. Case study: Developing an ideal aircraft seat contour using 3D scanning techniques. (Doctoral dissertation), Delft University of Technology, Delft, The Netherlands. Retrieved from repository.tudelft.nl/view/ir/uuid%3Aeedd25e6-c625-45e9-9d32-f818aa89c19d/
- IATA Sustainability & Economics. (2024a). *Air Passenger Market Analysis - July 2024*. Retrieved from <https://www.iata.org/en/iata-repository/publications/economic-reports/air-passenger-market-analysis-July-2024/>

- IATA Sustainability & Economics. (2024b). *Air Passenger Market Analysis - March 2024*. Retrieved from <https://www.iata.org/en/iata-repository/publications/economic-reports/air-passenger-market-analysis-march-2024/>
- Kamp, I., Kilincsoy, Ü., & Vink, P. (2011). Chosen postures during specific sitting activities. *Ergonomics*, 54(11), 1029-1042.
- Kilincsoy, U., Wagner, A., Bengler, K., Bubb, H., & Vink, P. (2014). Comfortable rear seat postures preferred by car passengers. Paper presented at the 5th International Conference on Applied Human Factors and Ergonomics.
- Kyung, G., & Nussbaum, M.A. (2008). Driver sitting comfort and discomfort (part II): Relationships with and prediction from interface pressure. *International journal of industrial ergonomics*, 38(5-6), 526-538.
- Mergl, C. (2006). *Entwicklung eines Verfahrens zur Objektivierung des Sitzkomforts auf Automobilsitzen*. (Doctoral dissertation), Technische Universität München, München, Germany. Retrieved from <https://d-nb.info/980332915/34>
- Molenbroek, J.F.M., Jürgens, H., Houtkamp, J.J., Burger, A.K.C., Steenbekkers, L.P.A., Dirken, J.M., . . . Huysmans, T. (1984-2020). *DINED Anthropometric Database*. gdvv1984, delstu1986, kima1993, geron1998, CAESAR, Goto (2011) Children's Heads, delstu2016, chile2016-workers. Retrieved from: <https://dined.io.tudelft.nl/>
- Noro, K., Naruse, T., Lueder, R., Nao-i, N., & Kozawa, M. (2012). Application of Zen sitting principles to microscopic surgery seating. *Applied Ergonomics*, 43(2), 308-319.
- Park, S.J., Kim, C.-B., Kim, C.J., & Lee, J.W. (2000). Comfortable driving postures for Koreans. *International journal of industrial ergonomics*, 26(4), 489-497. doi:10.1016/S0169-8141(00)00020-2
- Richards, L.C. (1980). On the psychology of passenger comfort. Human Factors in Transport Research (Based on the Proceedings of the International Conference on Ergonomics and Transport), 2, 15-23.
- Smulders, M., van Dijk, L., Song, Y., Vink, P., & Huysmans, T. (2023). Dense 3D pressure discomfort threshold (PDT) map of the human head, face and neck: A new method for mapping human sensitivity. *Applied ergonomics*, 107, 103919. doi:10.1016/j.apergo.2022.103919
- Van der Grinten, M.P., & Smitt, P. (1992). Development of a practical method for measuring body part discomfort. *Advances in industrial ergonomics and safety*, 4(635), 311-318.
- Vink, P., & Brauer, K. (2011). *Aircraft Interior Comfort and design*. Boca Raton, USA: CRC Press.
- Vink, P., Franz, M., Kamp, I., & Zenk, R. (2012). Three experiments to support the design of lightweight comfortable vehicle seats. *Work*, 41(Supplement 1), 1466-1470.
- Zemp, R., Taylor, W.R., & Lorenzetti, S. (2015). Are pressure measurements effective in the assessment of office chair comfort/discomfort? A review. *Applied ergonomics*, 48, 273-282. doi:10.1016/j.apergo.2014.12.010

- Zenk, R. (2008). *Objektivierung des Sitzkomforts und seine automatische Anpassung*. (Doctoral dissertation), Technische Universität München, München, Germany.
Retrieved from <https://mediatum.ub.tum.de/doc/656298/>
- Zenk, R., Franz, M., Bubb, H., & Vink, P. (2012). Spine loading in automotive seating. *Applied Ergonomics*, 43(2), 290-295.

DESIGNING AIRCRAFT SEATS TO FIT THE HUMAN BODY CONTOUR

This chapter contains content from Chapter 4 and has been published as:

Hiemstra-van Mastrigt*, S., Smulders*, M., Bouwens, J. M., & Vink, P. (2019). Designing aircraft seats to fit the human body contour. In *DHM and Posturography* (pp. 781-789). Academic Press. *Shared first author.

ABSTRACT

To save fuel costs, light weight designs and materials are preferred for aircraft interiors. One of the challenges for designing aircraft seats is to reduce weight without compromising passenger comfort, or perhaps even while increasing comfort. This case study describes three different projects on light weight designs for aircraft seats, using 3D scanning methods to determine the ideal seat contour following the human body. The first project on upright sitting in an economy aircraft seat set out to collect imprints of the human body in a vacuum mattress by using a handheld 3D scanner to scan the body imprints and obtain a 3D surface. Subsequently, the different scans were superimposed in such a way that differences between the scans were minimised. Based on this “*ideal curvature*”, an adjustable seat pan concept was developed. A similar 3D scanning method was applied in two other projects: first, developing a prototype for passengers sleeping sideways in a premium economy class aircraft seat and, second, a human contour-based business class seating concept (as described in Chapter 4). This case study concludes with advantages of and recommendations for applying 3D scanning in similar projects.

5.1. Introduction to human body contour seat design

Aircraft seats contribute considerably to the weight of aircraft interiors. To save fuel costs, light weight designs (materials, configuration, shape) are preferred for aircraft interiors (Vink, Franz, Kamp, & Zenk, 2012). As the aircraft seat is one of the main factors affecting passenger comfort (Ahmadpour, Lindgaard, Robert, & Pownall, 2014), the challenge is to design a light weight aircraft seat without compromising on comfort. Studies by De Looze, Kuijt-Evers, and Van Dieën (2003), Zenk, Franz, Bubb, and Vink (2012), and Zemp, Taylor, and Lorenzetti (2015) indicate that increasing the contact area between human and seat can have a positive effect on comfort. This might be achievable by a seat that follows the human contour. Franz et al. (2011) explored a promising direction in reducing the amount of (heavy) foam in the backrest of a car seat by designing a back shell based on the human body contour. However, this contour cannot be copied into an aircraft seat directly because the posture of a car driver differs from the posture of an aircraft passenger. Therefore, more research is necessary to define a comfortable shape contour for aircraft seats.

This case study describes three different projects on how to design light weight aircraft seats that fit the human body contour by applying three-dimensional (3D) scanning methods (Franz et al., 2011) to determine the ideal seat contour following the human body. Three different types of aircraft seats were studied: Economy Class seat (Project EC) (Hiemstra-van Mastrigt, 2015; Kудay, 2018) Premium Economy Class seat (Project PEC) (Lam et al., 2014), and Business Class seat (Project BC) (Smulders et al., 2016; Chapter 4). As sleep is one of the most conducted activities on both short-haul and long-haul flights (Bouwens, Tsay, & Vink, 2017; Greggi, Rossi, Souza, & Menegon, 2012; IATA, 2016), and also one of the main reasons for premium class passengers to opt for the more comfortable but also more expensive premium seats, Projects PEC and BC focussed on facilitating sleep. Hence, upright sitting was studied in Project EC, whereas a lateral sleeping activity was studied in Project PEC and full-flat sleeping, as well as active and passive sitting activities were studied in Project BC.

5.2. Method of acquiring the human body contour through indirect 3D scanning

The following methods are based on the work of Franz et al. (2011) and have been described before in Hiemstra-van Mastrigt (2015) and Smulders et al. (2016) (Chapter 4).

5.2.1. Participants

Two groups of participants were recruited: 16 participants for Project EC and another 12 participants for both Projects PEC and BC. These participants were selected to vary in body dimensions and proportions as much as possible to get a representable reflection of the variety in aircraft passengers (see Table 5.1). The aim was to have an equal male/female distribution and participants of mixed ages (i.e. not only students).

Table 5.1 | Selected participants for Project EC and Projects PEC/BC to represent each of the 12 body dimension categories, defined by Stature x BMI, i.e., ranging from short and light female (~ P5) to tall and obese male (> P95).

BMI [kg/m ²]	Stature [m]					
	<1.65 (short)		1.65–1.80 (middle)		>1.80 (tall)	
	Male	Female	Male	Female	Male	Female
Light (< 23)		EC/PEC/BC	EC	EC/PEC/BC	EC/PEC/BC	EC
Middle (23-25)		EC	EC	EC/PEC/BC	EC/PEC/BC	
Overweight (26-30)		EC	EC/PEC/BC	EC/PEC/BC	EC/PEC/BC	PEC/BC
Obese (> 30)			EC/PEC/BC	EC	PEC/BC	

Population percentiles based on Molenbroek et al. (1984-2020). DINED Anthropometric database.

A group of 16 participants (8 male, 8 female) took part in Project EC. Their average body weight was 73 kg (SD = 14.9) and average stature was 1.716 m (SD = .099). Their mean age was not recorded; however, both young and elderly (65+ years) people participated in this study. During the data processing, it was noted that 4 participants (2 male, 2 female) out of 16 did not contribute to the overall scan (i.e. their body dimensions were too close to the average) and were therefore excluded from further analysis. Another group of 12 participants (6 male, 6 female) took part in both Projects PEC and BC. Their average body weight was 78 kg (SD = 18.2) and average stature was 1.755 m (SD = .126). For Projects PEC and BC, the mean age of participants was 30.6 years (SD = 16.1).

5.2.2. Setup and procedure

5.2.2.1. Equipment

To capture the body contours, participants of all three projects were asked to either sit or lay down on a vacuum mattress (VTI-Futur, 2000 × 800 × 150 mm). This mattress contains small Styrofoam balls that closely follow the body contour, and after draining the air out, the negative shape of the human body is fixed in the mattress. This negative imprint of the human contour was then scanned with a handheld 3D scanner (Project EC with an Artec Eva, Projects PEC/BC with an Artec L™). To support the vacuum mattress in Project EC, a wooden frame of the seat was built on a 3° angled floor (corresponding to the in-flight ‘*angle of attack*’ of the aircraft), with a fixed seat pan with 4° angle with respect to the inclined floor, and a seat pan-backrest angle of 108° (see Figure 5.1-A). In Projects PEC and BC, an aluminium-wood frame was used to support the vacuum mattress, with a fixed seat pan at 8° and featuring an angle adjustable backrest and leg rest (see Figure 5.1-B).

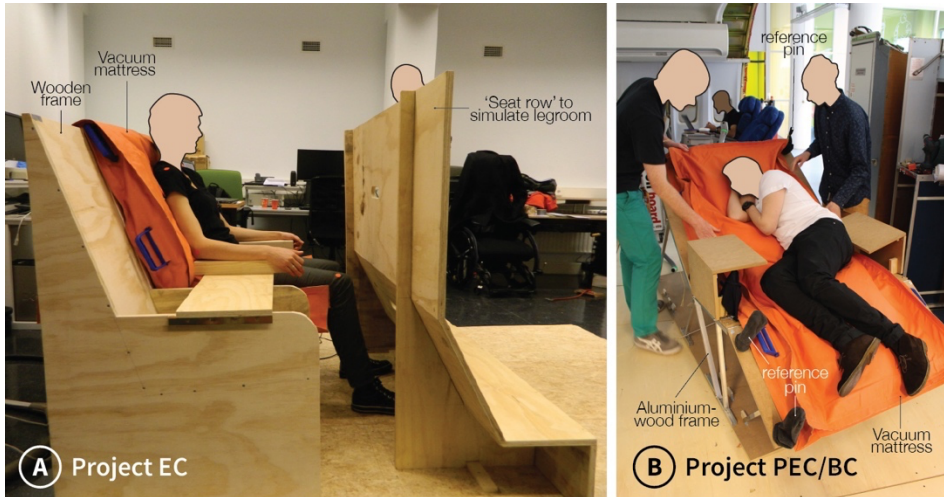


Figure 5.1 | (A) Setup for Project EC: basic wooden frame with 'seat row' in the front to simulate restricted legroom; (B) setup for Projects PEC and BC: angle adjustable aluminium-wood frame with armrests; participants in both projects were asked to either sit (A) or lay down (B) on the vacuum mattress (orange).

5.2.2.2. Protocol

In each of the three projects, one participant was measured at a time. In Project EC, the vacuum mattress was first put horizontally on the floor and smoothed out to evenly distribute the Styrofoam balls inside. Before lifting the vacuum mattress onto the wooden seat frame, it was vacuumed to keep the balls in place, although leaving some air inside to allow it to be pressed down to match the angles of the backrest and the seat pan. In Projects PEC and BC, the inclinable seat frame was placed horizontally and the vacuum mattress on the frame was smoothed out to evenly distribute the Styrofoam balls inside.

In all three projects, participants were then asked to sit or lay down on the vacuum mattress and to adopt a comfortable position in an upright (Project EC), lateral (Project PEC), or full-flat (Project BC) position. In Projects PEC and BC, the backrest and leg rest were inclined to meet the angles of passive, active, and sleeping activities for a premium economy class seat (Project PEC) and a business class seat (Project BC). Participants were then asked to wiggle to get a better imprint and were assisted by the researchers to shape the vacuum mattress around their body and to smooth out creases as much as possible. Then, the mattress was vacuumed to fix the participants' imprint. Thereafter the participant had to leave the seat, so the imprint of the body contour could be scanned with the handheld 3D scanner. This process was repeated for each of the participants.

5.2.3. Data processing

5.2.3.1. Project EC: Economy class seat

First, the body contour imprint was scanned (Figure 5.2-A) to obtain a virtual 3D surface of the imprint (Figure 5.2-B). Then, the axes of all the scans were placed equal to each other and the height of the scans was adjusted using orientation landmarks from the scans (i.e. the front of the armrests). The different contour scans were then superimposed using least squares so that the sum of squares of the differences among the scans was minimised (Figure 5.2-C). This method also allowed translation and rotation of the scans in the YZ-plane to create the best fit. The results from this ‘best-fitting’ method were combined into two surfaces: one inside contour (smallest) and one outside contour (largest). The surface between the legs was flattened and the overall surface was smoothed (manually) as well. As a final step, the values for left and right were averaged to symmetrise the surface.

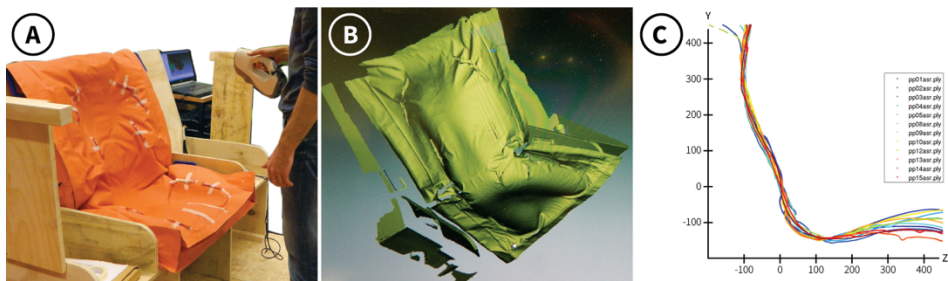


Figure 5.2 | Scanning process for Project EC, from left to right: (A) 3D scanning the body imprint; (B) virtual 3D surface of the imprint; (C) best-fit profile of the superimposed contour scans (n=12, each line represents one participant).

5.2.3.2. Projects PEC and BC: Premium economy and business class seat

All 3D scanned imprints were individually meshed. On top of this mesh, a point grid with fixed dimensions (11 × 9 points) was projected in Rhinoceros 3D Grasshopper (see Figure 5.3-A) on the backrest, seat pan, and leg rest individually, resulting in a Z-coordinate for each XY-coordinate on the grid (see Figure 5.3-B) of each part of the seat. The grid was deliberately limited in detail to avoid minor errors (e.g. irregular surfaces) and limit processing time but still have sufficient detail to get a representative shape. To ensure each grid was projected from the same origin, all scans were aligned using the vertical metal ‘reference’ pins—purposely put on the seat—as reference points (see Figure 5.1-B).

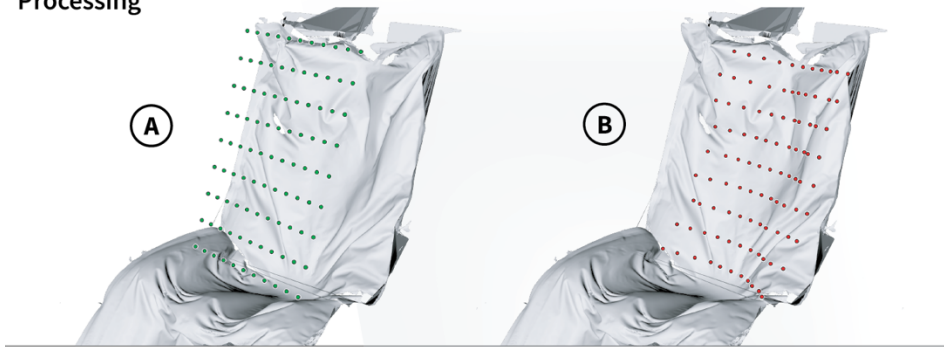
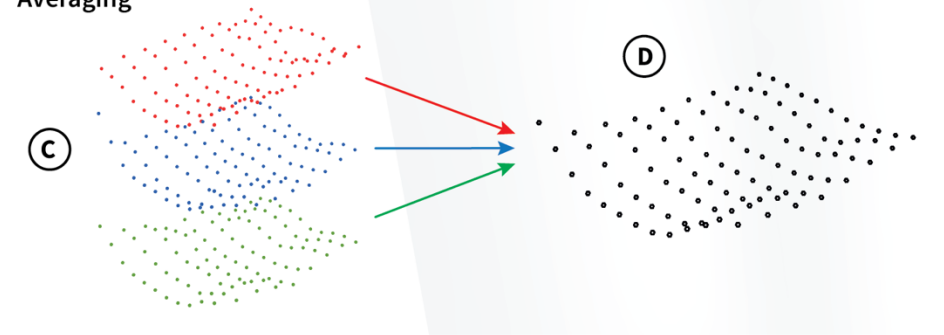
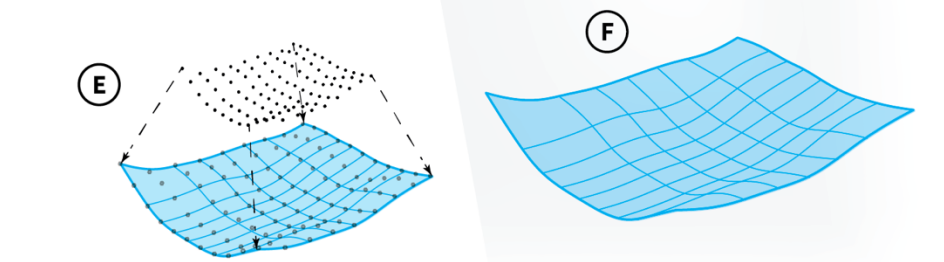
Processing**Averaging****Final surface**

Figure 5.3 | Visualisation of the post-scanning process for Projects PEC and BC; A–F indicate the different data processing steps. Image reproduced with permission of A. Vogel & A.L.E. de Vries.

For each posture (active, passive, sleeping) and each class (PEC/BC), all grid projections were positioned in the same plane (see Figure 5.3-C) to determine the mean of each point (see Figure 5.3-D). The resulting averaged point grid (see Figure 5.3-E) was then converted into a nonuniform rational B-spline (NURBS) surface (see Figure 5.3-F). This is a smooth 3D surface, representing the average human contour of the scanned participants in all the three sitting positions for PEC and BC, respectively, which can be imported and manipulated into every engineering grade computer-aided modelling program.

5.3. Results and application of 3D scans

The processed 3D scans were used as input for the redesign of an adjustable seat pan feature for Project EC, a lateral sleeping design concept for Project PEC and a full-flat sleeping solution for Project BC.

5.3.1. Adjustable seat pan feature for economy class seat

The ‘best-fit’ profile of the superimposed contour scans ($n=12$) is shown in Figure 5.4-A. Each line represents the body contour of one participant (vertical cut through the middle of the seat). The differences in the backrest contour are rather small (<55 mm) and could be compensated by the (relatively thin) backrest cushion. However, for the seat pan, the differences become larger toward the front because of a larger difference in popliteal height between the shortest and tallest passenger, resulting in a difference ranging between 55 and 100 mm. The seat pan cushion cannot accommodate this difference; therefore, an adjustable seat pan feature has been designed by Kuday (2018) (see Figure 5.4-B).

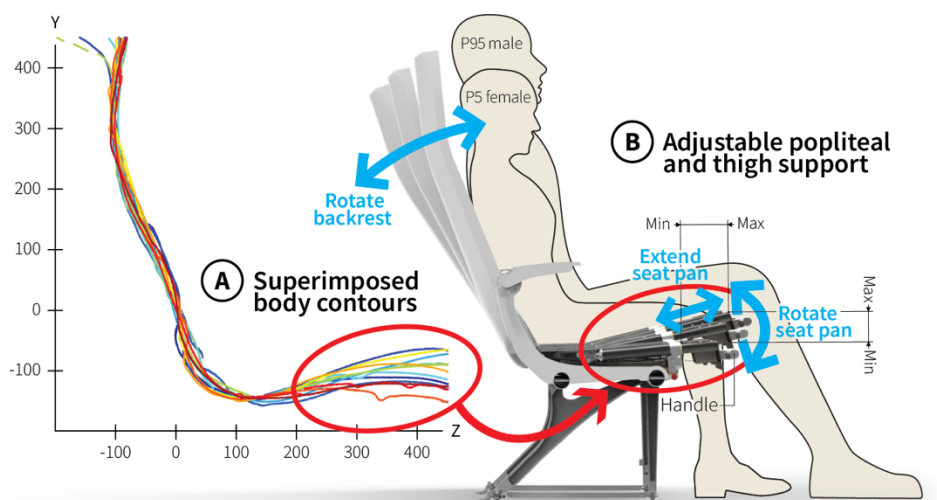


Figure 5.4 | (A) Superimposed body contours for Project EC (based on $n=12$, each line represents the body contour of one participant); (B) adjustable popliteal and thigh support feature to provide optimum support for both short and tall passengers (human figure indicative only). Image modified and reproduced with permission of M. Kuday and Aeroworks Composites B.V. (patent pending).

The designed seat pan concept features an adjustment handle that is positioned in the middle of the seat as shown in Figure 5.4-B. By pulling the handle forward, the passenger can adjust the length of the seat pan to support the popliteal area. The same handle can be pulled upward to adjust the angle of the seat pan when necessary. The mechanism can be retracted to its original position by pulling back the same handle. This creates optimal support for both short and tall passengers.

5.3.2. Lateral sleeping design concept for premium economy class seat

The challenge for Project PEC was to allow lateral sleep in a seat with limited recline, as lateral sleeping is most preferred (e.g. Haex (2004) and Smulders and Vink (2022) (Chapter 7)) and current aircraft seats lack head and lower back support (see Figure 5.5-A). The shape of the new designed backrest and seat pan follows the average ‘human contour’ scans of the active sitting position. To support lateral sleeping, the backrest features a moving midpiece, allowing it to translate downward (see Figure 5.5-B). This feature creates space for the shoulder, allowing the torso to be lateral oriented and the head to rest on the headrest, and provides support for the lower back.

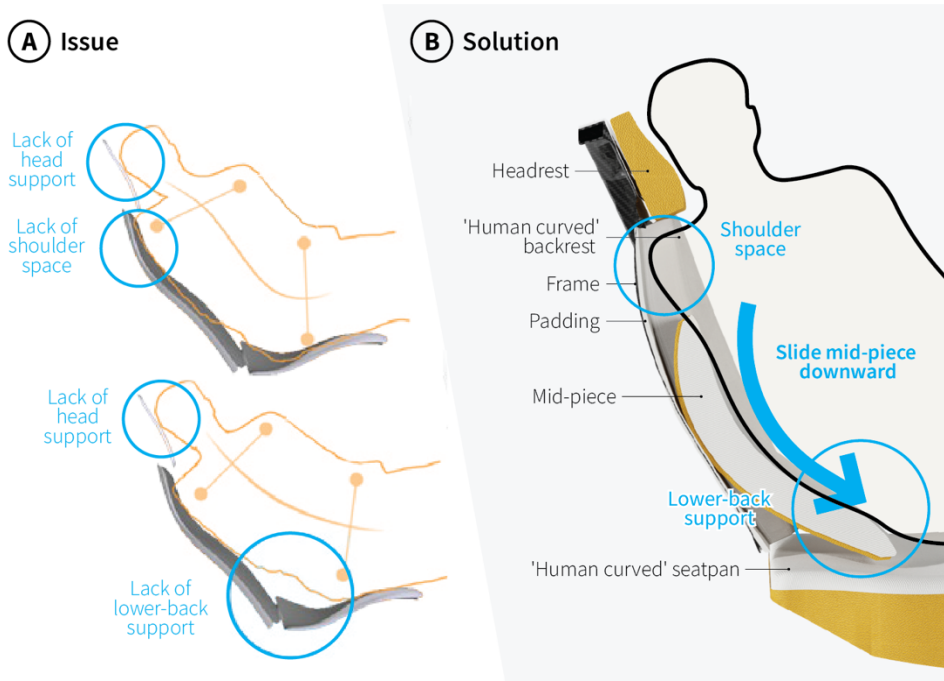


Figure 5.5 | Lateral sleeping design concept for PEC seat, featuring a midpiece in the backrest that can slide downward, facilitating a lateral sleeping posture by creating shoulder space, decreasing the distance between the head and the headrest, and supporting the lower back (human figure indicative only). Seat designed by A. Vogel, J.A. Stewart, A.J. Weiss, L.J. Lam, A.L.E. de Vries, and S.H.F. van Gils. Images modified and reproduced with permission of the designers.

5.3.3. Full-flat sleeping design concept for business class seat

The challenge for Project BC was to facilitate a full-flat bed experience, while in ‘seat mode’, the BC seat should follow the ‘human contour’ shape. Therefore, the seat pan and backrest shape were based on the average human contour 3D scans of the active sitting position. This human contour curved shell could be stretched by a linear actuator-driven scissor mechanism, transposing the surface from a curved seating position (see Figure 5.6-A) to a full-flat ‘bed’ surface (see Figure 5.6-B).

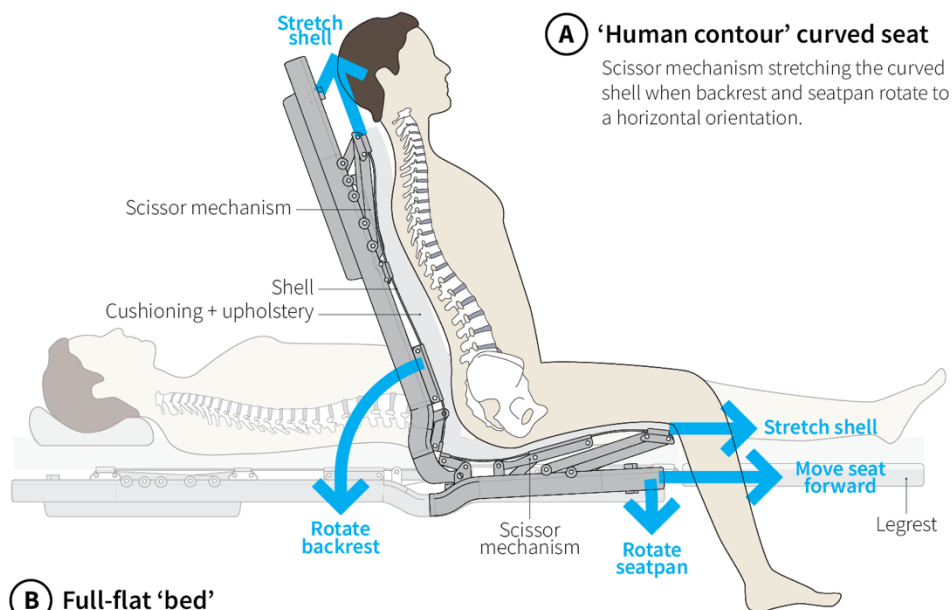


Figure 5.6 | Full-flat sleeping design concept for BC seat, featuring a linear actuator-driven scissor mechanism that can transpose the preformed shell from 'human contour' curved seat to a full-flat 'bed' (human figure and spine indicative only). Seat designed by K. Berghman, M. Koenraads, J.A. Kane, K. Krishna, T.K. Carter, and M. Smulders. Image modified and reproduced with permission of the designers.

5.4. Discussion and recommendations on designing aircraft seats to fit the human body contour

This case study described three different projects on how to design light weight aircraft seats that fit the human body contour. Project EC showed that carefully selecting participants proved to be a good method to limit the number of scans needed to develop an 'ideal' contour. During the processing of the scans, it appeared that four participants did not contribute to the end result, i.e., their body dimensions were too close to the average. Therefore, only participants with extreme body dimensions should be used to develop a seat contour. However, evaluation of the seat should be done with a wide variation of passengers, including those with 'average' body dimensions. Note should be taken, however, that the optimal method of collecting and processing scans is also dependent on the design of the seat and the applied materials, and further study is recommended.

Although the effect on comfort perception has not been studied in Project EC, the resulting human contour-based prototype seat from Project BC led to comfort and discomfort scores comparable with a traditional aircraft seat ($n=20$) (Smulders et al., 2016; Chapter 4). On the other hand, results from the study by Franz et al. (2011) show that having a shell based on the human contour does not necessarily increase the comfort

perception (n=25). The study by Franz et al. (2011) showed that further development was needed, which emphasises the importance of testing. Similarly, testing the adjustable seat pan concept of Project EC (n=34) proved that the adjustment and handle mechanism were not yet optimised and, specifically, that some female participants (3 out of 34) provided negative feedback about the positioning of the handle in the middle of the seat (Kuday, 2018). Testing is also needed because combining the 3D scan data can introduce new problems. For example, in Project EC, the smallest differences between the inside and outside contour were found using the least squares method, which allowed translation and rotation of the 3D scan in the YZ-plane. However, the resulting seat curvature might change the adopted body posture and is an example of possibly introducing a new problem.

Based on the results and lessons learned in the three projects described in this case study, the following six recommendations can be given for applying 3D scanning and modelling in similar projects:

1. Consider using 3D scanning when detailed anthropometrics are needed: Use of 3D scanning is advised when detailed and precise anthropometric data are needed, e.g. in seat design, such as double-curved contours of certain postures/activities of participants with certain body types. Although 3D scanning techniques can be very helpful, they will also generate a lot of data and take a lot of time and expertise to perform data processing on all the scans. Other tools, such as a kyphometer, could also provide information about the head, neck, and back contour (Nijholt, Tuinhof, Bouwens, Schultheis, & Vink, 2016) and require less effort to use.
2. Consider different activities and body postures in seat design: Activities that passengers perform strongly influence their body postures (e.g. Groenesteijn et al. (2014) and Kamp, Kilincsoy, and Vink (2011)); hence, the seat contour should facilitate different postures. Although only one posture (upright sitting) was scanned and analysed in project EC, three different postures were studied in Projects PEC and BC: active, passive, and sleeping activities (supine and lateral). Still, facilitating different postures in the same seat without adding too many adjustment options remains a design challenge.
3. 3D modelling requires decision-making of the designer/engineer: When merging different scans, their alignment needs to be optimised. This process will require decision-making by the designer/engineer and depends on the shape and materials of the seat. Considering extremes in populations is advised so that the method of creating an inner and outer contour (Project EC) is preferred over calculating an average contour (such as Projects PEC and BC).
4. Superimpose scans to compare them: As participants never sit exactly in the middle of the vacuum mattress, using fixed reference points to 'stack' or combine scan models is not ideal (Projects PEC and BC). Instead, to be able to interpret the results correctly, superimposing of models is advised, making them

'fit' as close to each other as possible (such as Project EC). This helps to see similarities and find differences among populations, allowing designers and engineers to make adequate decisions.

5. Combine the imprint scans with full body scans of participants: In this case study, only the imprint ('negative' contour) of the human body was scanned. Yet it will be possible to create a (positive) full DHM (Digital Human Model) if the imprint was to be combined with a full body scan of the participant while sitting in the vacuum mattress; e.g. by scanning the participant while sitting in the vacuum mattress; scanning the participant imprint in the mattress; and then fuse both scans into one full DHM and remove the excess of the vacuum mattress. The full DHM then contains additional data, such as the height of the arms for designing armrests or the thigh thickness for designing tray tables. This might also help the interpretation of the model from the imprint scan, such as where the contact of the human body with the seat surface ends.
6. Validate the seat design with (dis)comfort user tests: Ideally, not only the end result but also various versions of the design are tested during the design process. Similar to Hofmann (2018), who described that the car development process is an iterative process, Kilincsoy (2019) suggested an iterative circle of seat design. Professionals also emphasised the importance of an iterative design process in the research (Kok, Slegers, & Vink, 2016). In case of the seat curvature, which needs to fit closely to the human body, it is advised to test with multiple (virtual) human models who represent a large variety in body dimensions (see also Table 5.1) and to perform a final validation test with a diverse group of human participants for a longer duration, representative of the intended use.

5.5. Conclusion

The three projects described in this case study show that it is possible to design a seat contour based on human body contours using 3D scanning. However, translating the 3D scans into a 3D model and eventually a prototype seat also requires biomechanical analysis and decision making by the seat designer/engineer on material application and adjustability options of seat features, such as a lumbar support. DHM does, however, provide opportunities for seat manufacturers to provide a better fit to the human body, while at the same time reducing weight through the application of new materials and optimised space and surfaces.

5.6. Acknowledgements

The authors would like to thank all those involved in these 3D scanning research and design projects

Project EC: L.F.M. Kuijt-Evers, F. ter Haar, P. Eendebak, R. Könemann, M. Hoogenhout, M. Kuday, and R. Westerink. Project PEC: A. Vogel, J.A. Stewart, A.J. Weiss, L.J. Lam, A.L.E. de Vries, and S.H.F. van Gils. Project BC: K. Berghman, M. Koenraads, J.A. Kane, K. Krishna, T.K. Carter, R.H.M. Goossens. Projects PEC and BC: U.W. Schultheis, R.S. van der Horst, and H.F. Broekhuizen. Projects EC, PEC, and BC: B.J. Naagen.

Furthermore, the authors are very grateful to Royal TenCate NV for supplying materials for projects PEC and BC, and AMES Europe BV, the Dutch Ministry of Economic Affairs (EL&I-co financing), TNO (Netherlands Organization for Applied Scientific Research), Safran Seats US (formerly Zodiac Seats US LLC), and Aeroworks Composites B.V. for their financial support of these research and design projects.

5.7. References

- Ahmadpour, N., Lindgaard, G., Robert, J.-M., & Pownall, B. (2014). The thematic structure of passenger comfort experience and its relationship to the context features in the aircraft cabin. *Ergonomics*, 57(6), 801-815. doi:10.1080/00140139.2014.899632
- Bouwens, J., Tsay, W.-J.J., & Vink, P. (2017). The high and low comfort peaks in passengers' flight. *Work*, 58(4), 579-584. doi:10.3233/wor-172637
- De Looze, M.P., Kuijt-Evers, L.F.M., & Van Dieën, J.H.L. (2003). Sitting comfort and discomfort and the relationships with objective measures. *Ergonomics*, 46(10), 985-997.
- Franz, M., Kamp, I., Durt, A., Kilincsoy, Ü., Bubb, H., & Vink, P. (2011). A light weight car seat shaped by human body contour. *International Journal of Human Factors Modelling and Simulation*, 2(4), 314-326. doi:10.1504/ijhfm.2011.045002
- Gregghi, F., Rossi, N., Souza, G., & Menegon, L. (2012). Contributions from the activity analysis to the products development project: case study based on a project of innovation and comfort in aircraft's cabins. *WORK*, 41(Supplement 1), 55-60. doi:doi.org/10.3233/WOR-2012-0135-55
- Groenesteijn, L., Hiemstra-van Mastrigt, S., Gallais, C., Blok, M., Kuijt-Evers, L., & Vink, P. (2014). Activities, postures and comfort perception of train passengers as input for train seat design. *Ergonomics*, 57(8), 1154-1165.
- Haex, B. (2004). Back and bed: ergonomic aspects of sleeping. Boca Raton, FL, USA: CRC press. doi:10.1201/9780203022306
- Hiemstra-van Mastrigt, S. (2015). *Comfortable passenger seats: Recommendations for design and research*. (Doctoral dissertation), Delft University of Technology, Delft, the Netherlands. Retrieved from <https://repository.tudelft->

- nl.tudelft.idm.oclc.org/islandora/object/uuid:eedd25e6-c625-45e9-9d32-f818aa89c19d doi:10.4233/uuid:eedd25e6-c625-45e9-9d32-f818aa89c19d
- Hofmann, A.C. (2018). *From outside-in towards inside-out, an excursion to automobile design strategy for the future*. (Doctoral dissertation), Delft University of Technology, Delft, the Netherlands. doi: 10.4233/uuid:5b39f7c1-2907-4b77-85f4-f63f9965c0a2
- IATA. (2016). *IATA global passenger survey highlights*. Montreal, Canada: International Air Transport Association. Retrieved from iata.org/publications/store/Documents/GPS-2016-Highlights-Final.pdf.
- Kamp, I., Kilincsoy, Ü., & Vink, P. (2011). Chosen postures during specific sitting activities. *Ergonomics*, 54(11), 1029-1042.
- Kilincsoy, Ü. (2019). *Digitalization of posture-based Seat Design: Developing car interiors by involving user demands and activities*. (Doctoral dissertation), Delft University of Technology, Delft, the Netherlands. doi: 10.4233/uuid:419e4678-cb27-4c03-9725-7fb5b0fd3a12
- Kok, B.N.E., Slegers, K., & Vink, P. (2016). Essentials in the design process for creating comfort in vehicle seats. In *Design Process Components and Perceived Product Quality* (Vol. Doctoral dissertation, pp. 113-137). Delft, The Netherlands: Delft University of Technology.
- Kuday, M. (2018). *Designing a lightweight and comfortable aircraft seat*. (Master thesis), Delft University of Technology, Delft, The Netherlands. Retrieved from <http://resolver.tudelft.nl/tudelft.idm.oclc.org/uuid:77c6a83b-1c0b-4f2c-aad9-4c2e17e1efdd>
- Lam, L., Stewart, J., Vogel, A., Gils, S.V., Vries, A.D., & Weiss, A. (2014). *Improving the premium economy class seat to provide a better experience*. (Unpublished student report), Delft University of Technology, Delft, The Netherlands.
- Molenbroek, J.F.M., Jürgens, H., Houtkamp, J.J., Burger, A.K.C., Steenbekkers, L.P.A., Dirken, J.M., . . . Huysmans, T. (1984-2020). *DINED Anthropometric Database*. gdvv1984, delstu1986, kima1993, geron1998, CAESAR, Goto (2011) Children's Heads, delstu2016, chile2016-workers. Retrieved from: <https://dined.io.tudelft.nl/>
- Nijholt, N., Tuinhof, T., Bouwens, J., Schultheis, U., & Vink, P. (2016). An estimation of the human head, neck and back contour in an aircraft seat. *Work*, 54(4), 913-923. doi:10.3233/wor-162355
- Smulders, M., Berghman, K., Koenraads, M., Kane, J., Krishna, K., Carter, T., & Schultheis, U. (2016). Comfort and pressure distribution in a human contour shaped aircraft seat (developed with 3D scans of the human body). *WORK*, 54(4), 925-940.
- Smulders, M., & Vink, P. (2022). Sleeping postures in adults: a literature review. Paper presented at the 21st Triennial Congress of the International Ergonomics Association.
- Vink, P., Franz, M., Kamp, I., & Zenk, R. (2012). Three experiments to support the design of lightweight comfortable vehicle seats. *WORK*, 41(Supplement 1), 1466-1470. doi:10.3233/WOR-2012-0339-1466

- Zemp, R., Taylor, W.R., & Lorenzetti, S. (2015). Are pressure measurements effective in the assessment of office chair comfort/discomfort? A review. *Applied ergonomics*, 48, 273-282. doi:10.1016/j.apergo.2014.12.010
- Zenk, R., Franz, M., Bubb, H., & Vink, P. (2012). Technical note: Spine loading in automotive seating. *Applied Ergonomics*, 43(2), 290-295. doi:10.1016/j.apergo.2011.06.004

IMPLEMENTING FOAM SPRING TECHNOLOGY TO DESIGN A LIGHT WEIGHT AND COMFORTABLE AIRCRAFT SEAT PAN

This chapter has been published as:

Dangal, S., Smulders, M., & Vink, P. (2021). Implementing spring-foam technology to design a light weight and comfortable aircraft seat-pan. *Applied Ergonomics*, 91, 103174.

ABSTRACT

This chapter investigates whether foam spring technology in an aircraft seat pan can reduce weight and at the same time provide equal or better comfort.

Through literature studies and using an iterative design process a prototype seat pan was designed and developed using foam spring technology. The (dis)comfort of this seat was compared with a standard aircraft seat pan. Twenty-two participants were asked to sit in each seat for 90 minutes, completing a questionnaire every 15 minutes. At the end of each seating session pressure map recordings were made of the seat pans.

The results showed that the prototype seat pan has (on average) a significantly higher comfort for the first 30 minutes and at a 60 minute recording than the standard seat pan. The discomfort and long-term comfort were not significantly influenced. The pressure distribution on the prototype seat pan was significantly closer to an ideal pressure distribution than a conventional seat pan. In addition, the prototype seat pan had a significantly larger contact area and lower average pressure. The seat cushion weighs 20% less than a conventional seat cushion.

This study indicates that a seat pan design using foam spring technology can be lighter and more comfortable than conventional foam cushion materials. It is recommended to optimise the prototype seat further and conduct long-term (dis)comfort studies with a broader variation in participants' age.

6.1. Introduction

Air travel demand is estimated to double over 20 years (IATA, 2016). Even with such an increment, as a measure to mitigate global warming, the International Civil Aviation Organization aims to reduce 50% of the aviation emissions by 2050 (Maurice et al., 2009). One way to reduce emissions would be to decrease the overall weight of an airplane (Ordoukhanian & Madni, 2014), which decreases fuel usage and associated emissions, and additionally saves fuel costs for airlines. Especially for long-haul flights the impact of weight saving is high and therefore interesting (Filippone, 2012). Apart from weight savings, passenger comfort is important as well to airlines, as it is one of the decisive factors for passengers to “fly again with the same airline” (Vink, Bazley, Kamp, & Blok, 2012). Vink et al. (2012) and Ahmadpour, Lindgaard, Robert, and Pownall (2014) showed that seat comfort is one of the most influencing factors in overall passenger comfort, especially on long-haul flights (Vink & Brauer, 2011). Therefore, increasing the seat pan comfort is valuable for airline companies.

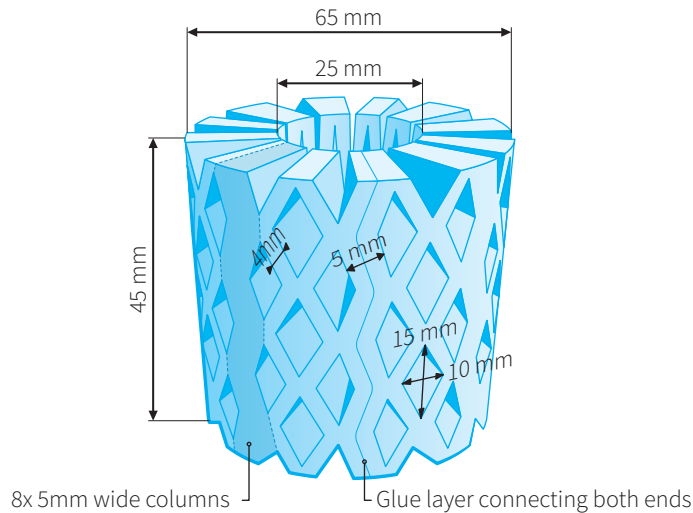


Figure 6.1 | Octaspring® foam spring unit. It is cut out of a foam sheet, folded circular and glued at the ends to form the tubular spring structure.

For comfort, the second most important element of the seat is the seat cushion of seat pan (after legroom) (Bouwens, 2018) and there are opportunities to increase comfort and reduce weight by using foam spring technology. Foam spring technology is a relatively new range of specially fabricated foams. Octaspring® is first described in a patent by Poppe (1980). It is a type of foam spring manufactured in eight (“octa”) sided tubes with lattice holes throughout the structure (see Figure 6.1). These can then be close-packed to create a layer that can be encased to form a structure such as a seat cushion. This type of foam spring is already used in bed mattresses and is easily available. Due to its availability and being already used in other products, Octaspring® foam spring is used for this study. This tubular foam spring is lighter than traditional foam structures with

similar firmness. By using different foam densities in the foam springs, it is possible to create different firmnesses of springs, and the modular nature of foam springs allows firmness to vary across the seat. Literature indicates that the firmness should differ for the various contact areas between the seat and human body to have an optimal comfort experience (Goossens, Teeuw, & Snijders, 2005; Vink & Lips, 2017; Zenk, Mergl, Hartung, Sabbah, & Bubba, 2006). In addition, due to its ‘*hollow*’ design, foam springs could be more efficient at moisture transport (i.e. have better breathability) than standard foam. This “*breathability*” quality in seats has a positive correlation with thermal comfort (Bartels, 2003). These properties mean foam spring technology provides a potential replacement for current moulded foams, which could increase comfort as well as reduce weight. However, no scientific study has been conducted to determine its effect on comfort and the weight savings when compared with traditional foams.

The first research question of this study is: can a foam spring technology in an aircraft seat pan reduce weight and at the same time provide equal or better comfort? Therefore, a new seat pan was designed and tested against a traditional seat pan. In order to design the new seat pan, firstly, literature is studied on pressure distribution, contour and firmness to determine the parameters for foam spring cushion.

6.1.1. Ideal pressure distribution

The correlation between the pressure distribution and comfort in car seats has been indicated by various papers (Fang, Gao, & Xie, 2016; Mergl, 2006; Zenk et al., 2006). Figure 6.2 shows an ideal pressure distribution for a car seat by Mergl (2006). An aircraft seat providing this ideal pressure distribution could result in higher passenger comfort and lower discomfort. The study was conducted with seats in which foam elements of different densities were placed to develop a pressure distribution close to the ideal one.

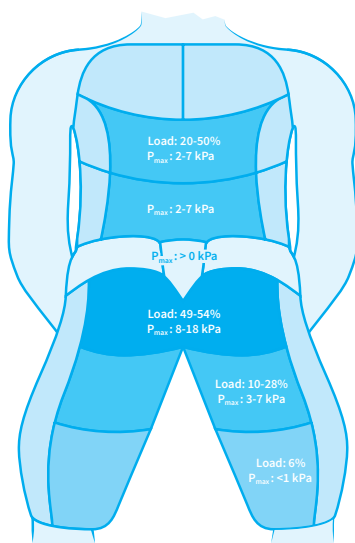


Figure 6.2 | Pressure distribution for a car seat as described by Zenk (2008) based on Mergl (2006).

6.1.2. Ideal contour

There are indications that a seat contour resulting in a large contact area is correlated to more comfort (De Looze, Kuijt-Evers, & Van Dieën, 2003; Fang et al., 2016; Franz et al., 2011; Zemp, Taylor, & Lorenzetti, 2015). One way to achieve this would be to use soft foam in the cushion to let the foam follow the entire contour shape of the user's buttocks. However, this means using large volumes of foam; resulting in increased weight. Another option would be to use a shaped contour shell derived from the human body and use inflatable cushions to fill gaps between P5 female to P95 male (Franz et al., 2011). Similarly, Smulders et al. (2016) (Chapter 4) showed that lower mean pressure between human and seat pan could be achieved by using a human contour shaped aircraft seat. It can be assumed that foam springs can also act as cushioning material to produce a similar effect.

Hiemstra-van Mastrigt (2015) described seat contours based on participants with a large variety in anthropometric dimensions (see Figure 6.3). Wang, Cardoso, and Beurier (2018) used cylinder pistons to create a contour profile based on an optimal pressure distribution. These profile models were used as qualitative guidance for the prototype seat pan contour.

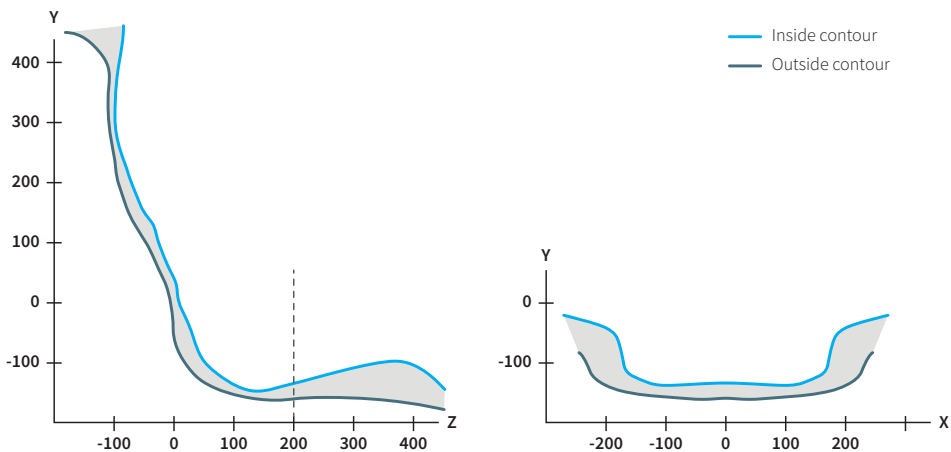


Figure 6.3 | Combined contour profile side view (left) and front view of the seat pan surface vertical cut through at Z=200 (right) (from Hiemstra-van Mastrigt (2015)) (n=12). The dark blue line is the outside (largest) surface, and light blue line is the inside (smallest) surface.

6.1.3. Cushioning firmness

In general, a softer cushion (lower stiffness) is often considered more comfortable than a firmer cushion (Ebe & Griffin, 2001; Fang et al., 2016). A soft cushion also increases contact area (Fang et al., 2016) and increases tolerable sitting time (Wang, Pu, & Liu, 2014). However, a very soft cushion which is not thick may not be able to support heavy loads and has an increased chance of “*bottoming out*” (buttocks ‘*feeling*’ the hard bottom plate of the seat), leading to discomfort (Ebe & Griffin, 2001).

In addition to the overall firmness of the cushion, the sensitivities of the buttocks and the upper leg differ, with the front thigh being more sensitive than the middle and back of the upper leg (Vink & Lips, 2017). This might mean that the firmness should differ for the various contact areas between the seat and the human body to give the occupant an optimal comfort experience with a firmer cushion in less sensitive areas and softer in more sensitive areas (Smulders et al. (2016), see Chapter 4).

6.1.4. **Foam spring seat cushion design**

The decisions on design parameters such as the number of layers (see Figure 6.4), exact firmness distribution (see Figure 6.5) and exact contour (see Figure 6.6) are guided by literature from §6.1.1 to §6.1.3. The form of the seat shell follows the ‘outer contour’ as described by Hiemstra-van Mastrigt (2015). Various foam configurations were made and adapted based on user feedback and pressure distribution recordings in an iterative design process. It is recognised that these parameters may not yet be optimal. However, if a prototype seat pan results in an increase in comfort, it opens possibilities to improve the seat further to make it more light weight and more comfortable.

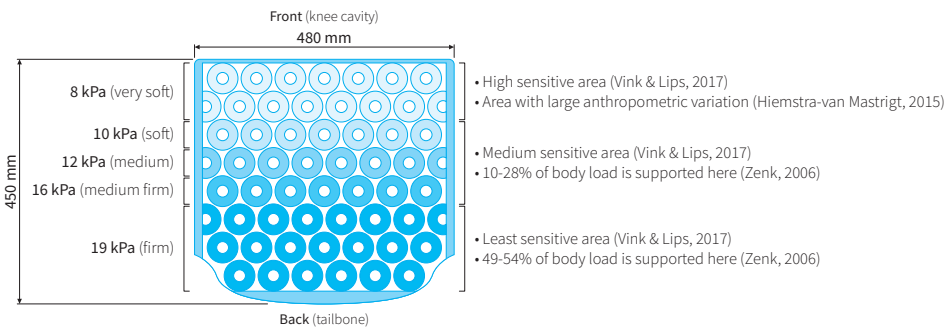


Figure 6.4 | Top-view representing the firmness distribution of foam springs in the prototype seat pan. Please note that the given firmness value (kPa) is taken before the foam is manufactured into a foam spring. The actual firmness of a foam spring is half of the stated firmness.



Figure 6.5 | Side-view of the prototype seat pan showing the layer composition of different foams.

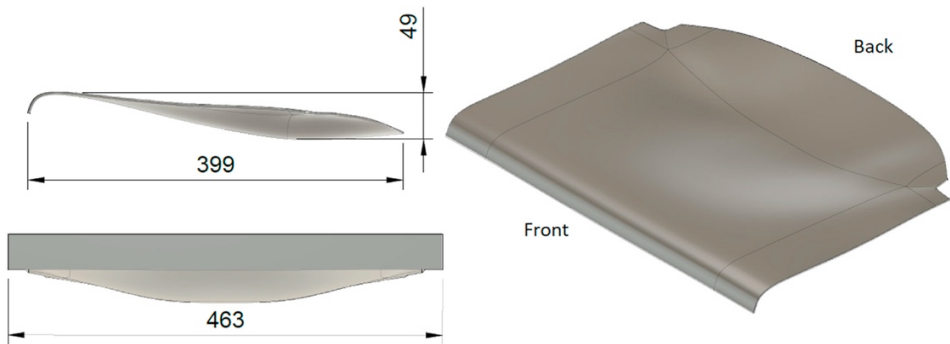


Figure 6.6 | Seat pan contour for the baseplate underneath the cushioning, side view (bottom left), back view (top left), orthographic view (right). Measurements are in mm.

6.2. Method and materials

6.2.1. Study setup

Two identical prototype seat pans (Figure 6.7) were developed using the specifications mentioned in §6.1.4 and covered with a thin white fabric. Hard foam was machined to the contour in Figure 6.6 to form the base of the seat pan. This was attached firmly to the seat frame (Recaro 3510 A) and the prototype seat cushion was firmly attached to the seat pan base. Both attachments were done with double sided foam tapes (Tesa 4952).

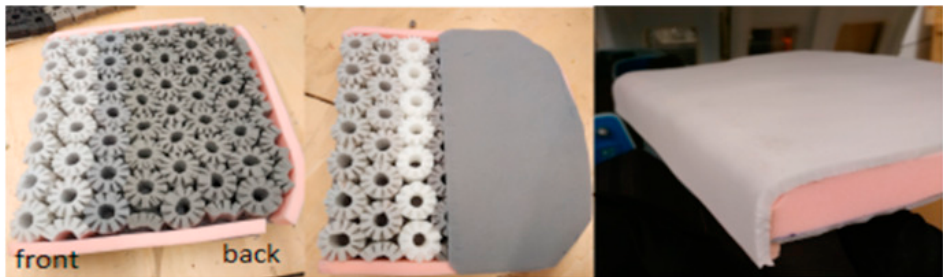


Figure 6.7 | Seat prototype. Foam spring distribution (left), firm layer addition (centre), final cushion without upholstery (right).

Additionally, the upholstery of two Recaro economy class seat pans (Recaro F2RE0134) was replaced with the thin white upholstery in order to minimise visual influence during the study. These seat pans were used as a reference condition in the study.

The study was conducted in a Boeing 737-500 airplane cabin at the campus of the Delft University of Technology to simulate a realistic in-flight sitting experience. Temperature and humidity were kept at a typical aircraft cabin temperature between 19–23° (Space, Johnson, Rankin, & Nagda, 2000) and a humidity of 40–50% respectively. This was done by setting the temperature of on-board heaters to 22 °C and (de)humidifier to 45%. The temperature and humidity were crosschecked every 15 minutes next to each participant during the study using a Roline A1 temperature and humidity sensor.

The seat pitch was set to 74 cm (29") and the seat pan height to 51 cm. All the seat backrests were fixed in the Taxi, Take-off and Landing (TTL) position (the most upright position in the seat). The four seats were placed at the window sides to keep the environmental variable constant for all participants in each seat (see Figure 6.8). Two XSENSOR LX100 pressure mats were calibrated and used for measuring the pressure distribution in each seat for each participant.

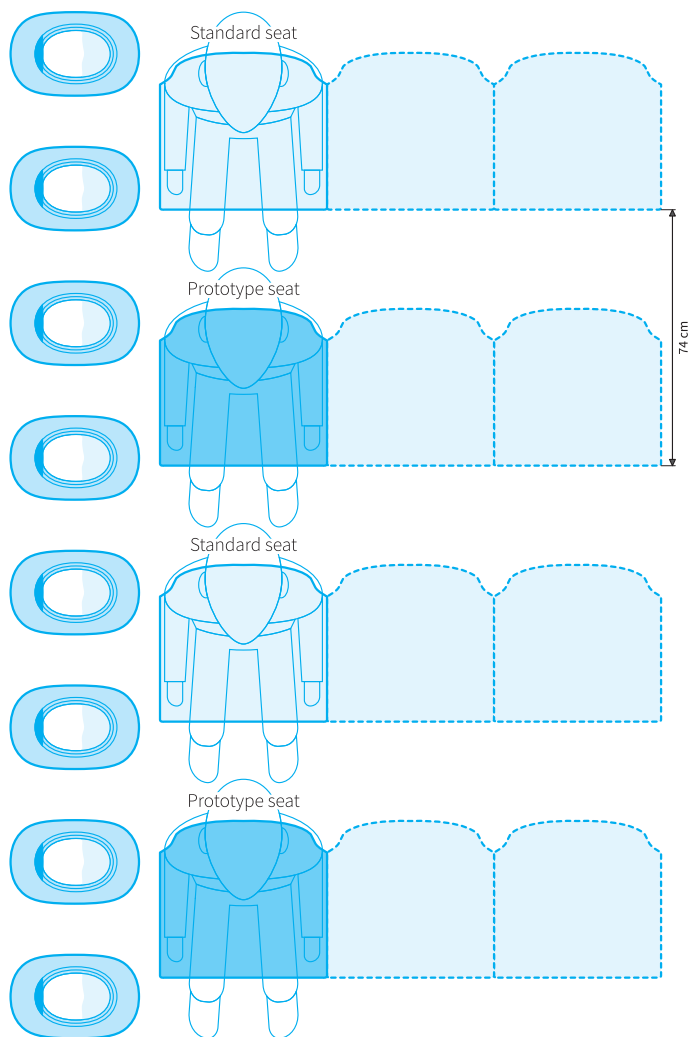


Figure 6.8 | Seating setup in the Boeing 737-500 fuselage.

The questionnaire document and pen were placed in the seat pocket and the participants were allowed to take either a phone or a book with them. Participants were requested to conduct the same activity in both seats (e.g. reading a book, using a phone or resting in both seats).

6.2.2. Participants

During the recruitment process, any interested participant was asked to report their weight, stature and gender. Using this information, 22 participants (13 male, 9 female) aged between 19 and 29 years were selectively chosen to have a large distribution of stature and Body Mass Index (BMI) (see Table 6.1).

Table 6.1 | Anthropometric measurements of participants (n=22).

		Mean	SD
Male (n=13)	Weight [kg]	75.3	8.5
	Stature [cm]	179.7	9.3
	BMI [Kg/m ²]	23.5	3.2
Female (n=9)	Weight [kg]	62.2	10.2
	Stature [cm]	165.3	7.4
	BMI [Kg/m ²]	23.0	5.0
All (n=22)	Weight [kg]	70.0	11.1
	Stature [cm]	173.8	10.8
	BMI [Kg/m ²]	23.3	3.9

6.2.3. Procedure

The study was conducted with up to four participants per session, each initially seated on either a standard or prototyped seat pan. The order was systematically changed among participants. Before the study, participants were informed on the procedure and were asked to sign a consent form. After signing, participants' anthropometric measurements were determined following the DINED procedure (Molenbroek et al., 1984-2020).

Each participant was seated in both the standard and prototype seat pan for 90 minutes. Drinks and snacks were provided around the 45-minute mark by an actor playing a Flight Attendant (see Figure 6.9). During the study, the participants were not allowed to talk or stand, change the backrest position or use the tray table, but were allowed to read a book, or use a cell phone, or rest during the study. After the end of first round, there was a 10-minute break before the second round was conducted. At the end of each round, a recording of the pressure distribution on the seat pan was made of each participant with the XSENSOR LX100 pressure mat.



Figure 6.9 | An actor playing a flight attendant serving drinks and snacks in a B737-500 fuselage.

6.2.4. Measurements

6.2.4.1. Local perceived discomfort measurement

Discomfort was recorded using a modified version of the local perceived discomfort (LPD) method (Van der Grinten and Smitt (1992) and Corlett and Bishop (1976)). A body map consisting of 7 regions (see Figure 6.10) was presented in the questionnaire in which participants were asked to give a score on a LIKERT scale ranging from 1 to 7 (1 = “no discomfort”; 7 = “severe discomfort”). Participants were asked to complete the LPD questionnaire at the first contact ($t = 0$ minutes) and after every 15 minutes during the 90 minute duration ($t = 0, t = 15, t = 30, t = 45, t = 60, t = 75, t = 90$ minutes). The difference in discomfort of each body part was tested between the two seats using a Wilcoxon signed rank test ($p < .05$) for paired observations (IBM SPSS Statistics 25); this analysis was conducted at each time interval.

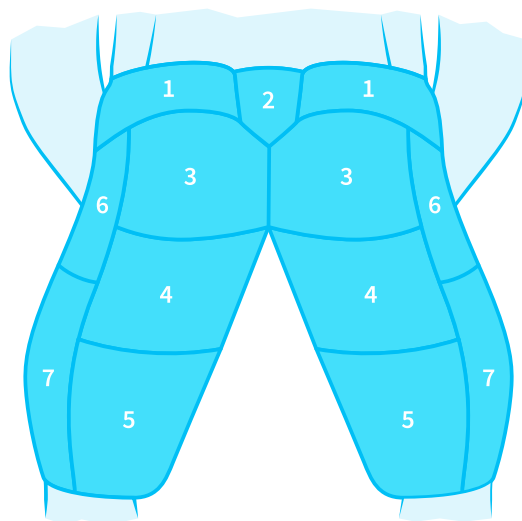


Figure 6.10 | Body Map to measure LPD (based on Van der Grinten and Smitt (1992) and Corlett and Bishop (1976)).

6.2.4.2. Comfort, discomfort and experienced firmness measurement

As Helander and Zhang (1997) made a distinction between sitting discomfort and sitting comfort, both aspects are studied. At 15 minute intervals ($t = 0, t = 15, t = 30, t = 45, t = 60, t = 75, t = 90$ minutes), the participants were asked to rate their overall comfort using a LIKERT scale rating from 1 to 9 (1 = *very uncomfortable*; 9 = *very comfortable*), and overall discomfort using a LIKERT scale rating from 1 to 9 (1 = *no discomfort*; 9 = *very severe discomfort*). Additionally at the same time interval, participants had to complete scores on comfort related statements; “*I find the firmness of the seat (too soft –too firm)*”, “*I feel sweaty between my buttocks and the seat*”, “*I feel uneasy*”, “*I like the chair*”. A space was provided for participants to make any additional remarks.

At the end of the study, having experienced both seats, the participants were asked to give a preference for one of the two seats imagining that they would sit long-

term (>4 hours) during a flight and add a reason for that. For this question, the participants were first allowed to sit on the previous seat again before answering this question.

Internal consistency was determined using Cronbach's alpha test. The ratings of statements were tested for significance ($p < .05$) between the prototype seat and the standard seat using the Wilcoxon signed rank test for paired observations.

6.2.4.3. Pressure mapping

At the end of each 90-minute sitting session, recordings of the pressure distribution were made of each participant. The pressure map values were taken after 30 seconds of sitting. During this process, participants were asked to sit in a comfortable position with their feet flat on the ground and their back rested against the backrest, which was kept in the TTL position.

The pressure map data were exported to Excel and a single rectangular box was drawn covering all the non-zero pressure values. During this process, any abnormal pressure reading outside potential seating areas was ignored. This box was then segmented into three equal areas (see Figure 6.11) and the total force in each area was calculated. This force (F_n) at each area was converted into a percentage of total body weight on the seat ($F_n/\text{body-weight}$), this gave the pressure distribution across the seat pan. This pressure distribution of each area of the prototype seat pan was tested for significance against the standard seat pan using a t-test. This was then compared to the ideal pressure distribution (Mergl, 2006). In addition, the average pressure in each area, contact area and peak pressure were calculated and tested for significant differences between the standard seat pan and the prototype seat pan.

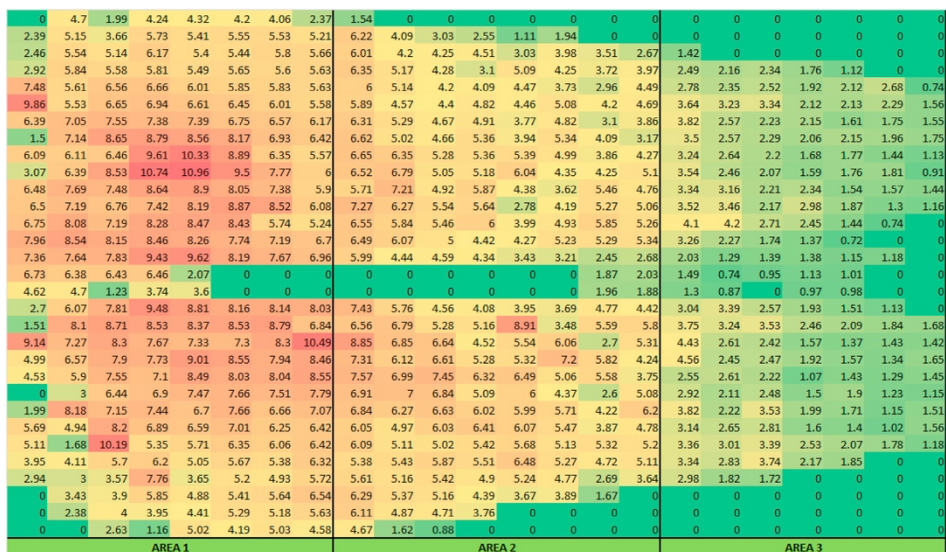


Figure 6.11 | Pressure map data segmentation in excel. Area 1 (A1) = Buttocks area, Area 2 (A2) = Mid thigh area, Area 3 (A3) = Front thigh area.

6.3. Results and discussion

6.3.1. Local perceived discomfort

The results of Local Perceived Discomfort of the different areas showed a general trend of increasing discomfort in all areas through time for both the standard and the prototype seat pan. There was no significant difference in discomfort at any time ($t = 0$ to $t = 90$ minutes) at any area between the standard and prototype seat pan.

6.3.2. Overall perceived discomfort

The overall mean perceived discomfort of the prototype and standard seat pan is shown in Figure 6.12. Although the graph shows the overall perceived discomfort of the prototype is lower than that of the standard seat pan, a significant difference is only found at 60 minutes from the start ($p = .035$) (see Table 6.2).

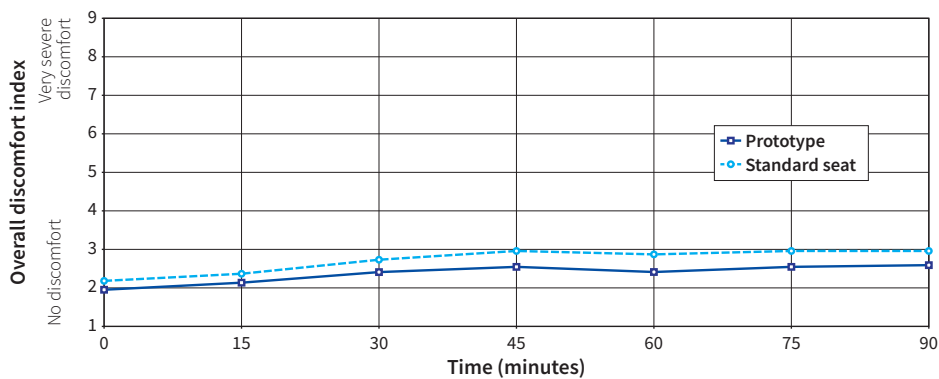


Figure 6.12 | Mean discomfort rating of standard and prototype seat pan against time (n=22).

Table 6.2 | Wilcoxon signed-rank test for overall perceived discomfort (standard seat vs prototype). (null hypothesis rejected at significance $p \leq .05$) (n=22). (Significant results are marked by asterisk).

Time (t)	0 min	15 min	30 min	45 min	60 min	75 min	90 min
Z-value	-1.165	-.929	-1.064	-1.263	-1.812	-.915	-.615
p-value (one-tailed)	.122	.177	.143	.103	.035*	.180	.269

6.3.3. Overall perceived comfort

The overall perceived comfort of the prototype and standard seat pan is shown in Figure 6.13. From the graph, it can be observed that on average, comfort of the prototype seat pan tends to be rated higher than the standard seat. A significant difference was found between the standard seat and prototype seat pan during the first 30 minutes ($t = 0$, $t = 15$, $t = 30$) and at $t = 60$ (see Table 6.3).

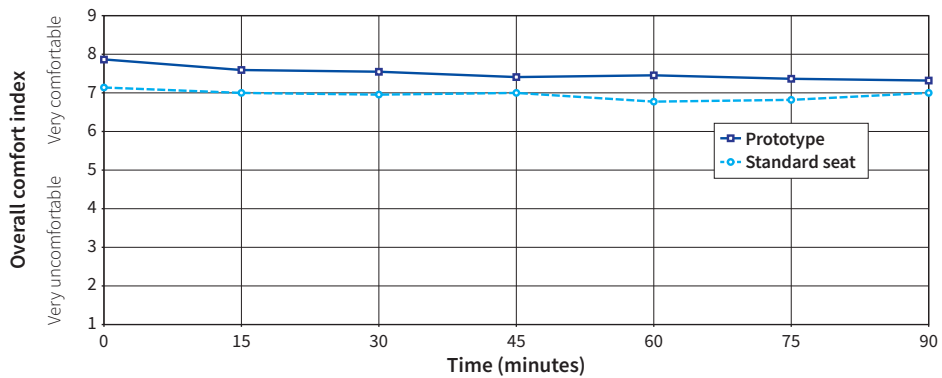


Figure 6.13 | Mean comfort rating of standard and prototype seat pan against time (n=22).

Table 6.3 | Wilcoxon signed-rank test for overall perceived comfort (standard seat vs prototype) (n=22). Null hypothesis rejected at significance $p \leq .05$. Significant results are marked by asterisk.

Time (t)	0 min	15 min	30 min	45 min	60 min	75 min	90 min
Z-value	-2.830	-1.789	-1.941	-1.135	-2.040	-1.363	-.534
p-value (one-tailed)	.002*	.037*	.026*	.127	.021*	.087	.298

6.3.4. Cushioning firmness

The overall perceived firmness of the prototype and the standard seat pan are shown in Figure 6.14 where on average, the firmness of the prototype tends to be rated lower than the standard cushion. Participants scored a significant difference in firmness between the standard cushion and the prototype at all times (see Table 6.4).

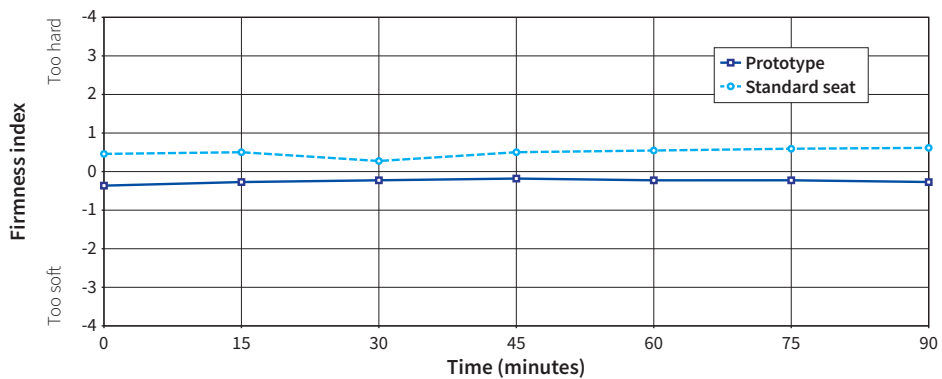


Figure 6.14 | Mean perceived firmness rating of standard and prototype seat against time (n=22).

Table 6.4 | Wilcoxon signed-rank test for perceived firmness of the cushion (standard seat vs prototype) (n=22). Null hypothesis rejected at significance $p \leq .05$. Significant results are marked by asterisk.

Time (t)	0 min	15 min	30 min	45 min	60 min	75 min	90 min
Z-value	-2.794	-2.896	-2.215	-2.627	-3.039	-2.951	-2.959
p-value (one-tailed)	.003*	.002*	.013*	.004*	.001*	.002*	.002*

6.3.5. Seat preference and user remarks

The overall seat preference for >4 hours of seating was equal (11 preferred the prototype vs 11 preferred the standard) (see Figure 6.15). Three participants with history of back problems preferred the standard seat and mentioned that they felt that their back was more “supported” with a firmer seat than a softer one. Two participants who chose the standard seat mentioned that whilst they felt more comfortable in the prototype seat, they may like a firmer one (standard seat) for over 4 hours sitting. Two participants who preferred the standard seat mentioned that the seat may be “too soft” for longer flights.

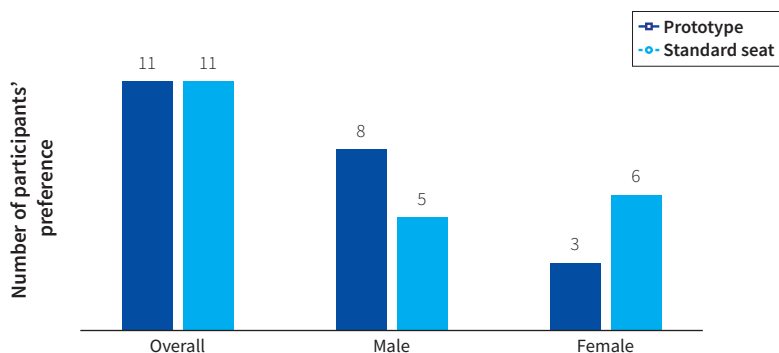


Figure 6.15 | Seat preference between standard and prototype seat pan for >4 h seating (n=22).

Participants who chose the prototype seat used key words like “very comfortable”, “gave warm feeling”, “makes me feel relaxed”, “wraps around body nicely”, “good support from all sides”, “easier to sleep in”, “slight element of sinking which was comfortable and helped me maintain a good posture”, and “found it thicker but also more comfortable on long-term”. Three participants found the seat “softer”, and therefore “more comfortable”.

8 out of 12 male participants preferred the prototype seat whilst 3 out of 9 female participants preferred the prototype seat. Why most males preferred the prototype seat and most females the standard might be coincidental, but would be interesting to study further.

6.3.6. Pressure distribution

The pressure distribution is compared with the ideal pressure distribution (Mergl, 2006) in Figure 6.16. Table 6.5 shows that significant differences were found in the pressure distributions under the buttocks ($p = .008$) and the front thighs ($p = .01$), favouring the prototype seat pan as it is closer to the ideal pressure distribution. This supports the general findings of higher comfort in the prototype seat pan than in the standard seat pan.

However, the pressure distribution of the prototype seat is still not close to the ideal pressure distribution. This may be due to several factors. Firstly, this is an aircraft seat and the position is more upright than in a car seat of the study of Mergl (2006). The maximum pressure might be more shifted to the front as in a more upright position the centre of gravity of the occupant moves forward. This may explain higher pressures in the front and middle thigh areas, and lower pressure in the buttocks area.

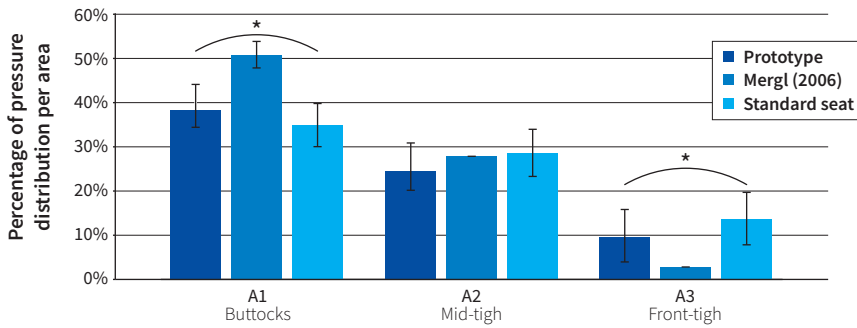


Figure 6.16 | Comparison of pressure distribution of 3 areas in standard (old) vs prototype (new) seat pan, (A1 = Buttocks, A2 = Mid-thigh, A3 = Front-thigh, see Figure 6.11) vs ideal pressure distribution (Mergl, 2006). Significant differences between the prototype and standard seat are marked by an asterisk (see Table 6.5).

Table 6.5 | Two tailed T-test for pressure distribution (PD), peak pressure and contact area of standard seat vs prototype seat pan (n=22). Null hypothesis rejected at significance $p \leq .05$. Significant results are marked by an asterisk.

	PD of A1 (Buttocks)	PD of A2 (Mid Thigh)	PD of A3 (Front Thigh)	Contact Area	Average Pressure	Peak Pressure
<i>p</i> -value	.008*	.058	.016*	.014*	.003*	.350

There was also a significant difference in contact area ($p = .014$) and average pressure ($p = .0025$); favouring the larger contact area and the lower average pressure for the prototype seat (Table 6.5). This supports the relation indicated by Fang et al. (2016) where a higher contact area is suggested to be linked to higher comfort and a lower average pressure.

There was no significant difference between the peak pressure of the standard and the prototype seat pan (see Figure 6.17 & Table 6.5). A possible explanation is that in both cases no 'bottoming out' is found.

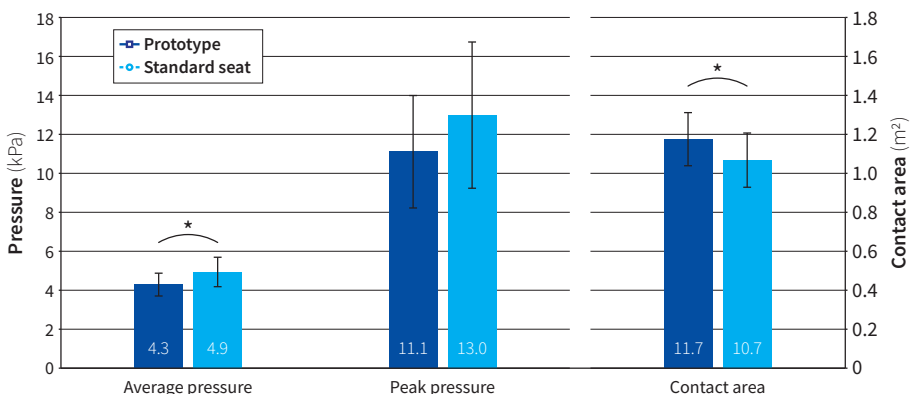


Figure 6.17 | Average pressure, peak pressure and contact area comparison between standard and prototype seat. Sig. diff. between prototype and standard seat are marked by asterisk (see Table 6.5).

6.3.7. Cushion weight reduction

The prototype seat cushion weighs 530 grams (g) without fire-blocker. It can be assumed that 60–70 g will be added to this due to fire blocker, thereby arriving at a weight of 600 (± 10 g) grams in total. The currently available seat cushion for this seat weighs 750 g, which means a reduction of 150 g (20%) in weight. In an Airbus A330-300 with 259 economy seats, this results in a total weight reduction of 39 kg per aircraft. This is comparable to a typical total baggage allowance of 30 kg per person (23 kg luggage + 7 kg hand luggage), which at a glance do not seem very significant. However, considering every kg of weight reduction reduces the carbon emission by about 400 kg yearly (Schäfer, Evans, Reynolds, & Dray, 2016), this sums up to 15.6 tonnes of CO₂ emissions reduction yearly per aircraft. In addition, this reduction in weight and improvement in comfort opens a possibility for foam spring technology to be implemented in seats not just for aircraft, but the entire transportation industry.

6.3.8. Study limitations

There are several limitations in this study: the two prototype seats were made manually by the researcher and may not have the professional level of finishing (e.g. gluing, cutting and trimming). This may influence the overall comfort as well as the weight of the seat. Furthermore, the prototype seat was not covered with a fire-blocker whilst the standard cushion had a fire-blocker, this may also have influenced the result. In addition, the study was conducted in 90 minute seating sessions and this may not be representative for the comfort/discomfort experience during a long-haul flight (> 4 h). Furthermore, the study was conducted in seats in a TTL position and the influence of the seat pan at the fully reclined position has not been studied. Moreover, the participants' age range was between 19 and 29 years, and the sample had a relatively low BMI. The sample is thus not representative for the whole population in terms of age and BMI. Therefore, results of the study may only apply to this specific demographic group.

There may also be inconsistency in pressure map readings due to variation in “comfortable” postures by the user. In addition, data processing of the pressure matrix into area segments (A1, A2 & A3, see Figure 6.12) was done manually and could be prone to human errors. Nevertheless, the experiment was a within subject design and significant differences were found between the seats, which indicates a promising direction of development. Studying the long-term effects with other age groups and including a broader range in BMI is recommended.

6.3.9. Future design improvement and research

Considering the survey and user feedback in §6.3.1 and §6.3.2, it is recommended to develop a seat with a slightly increased firmness in the front area of the seat pan (from 8 to 12 kPa) and the top layer (from 8 kPa to 10 kPa) during the next iteration of the design (see Figure 6.18). In addition, the next iteration should be made professionally and include a fire-blocker.

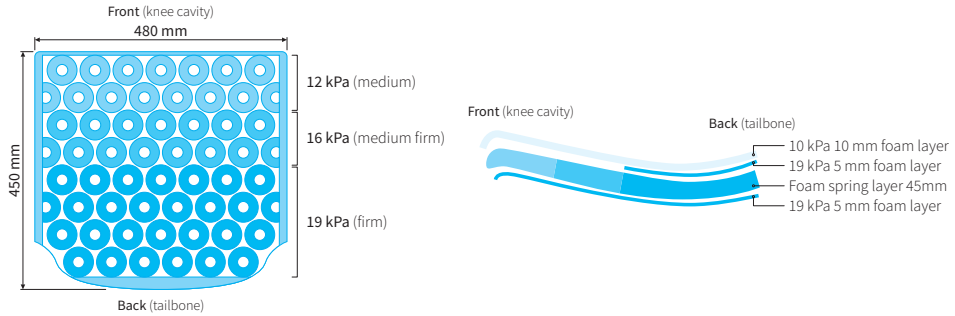


Figure 6.18 | Proposed design for next iteration.

It was found that there was no significant change in discomfort but a significant improvement in comfort, so it is important to use comfort and discomfort questions or questions linked to these aspects. Probably for a good seat the discomfort scale is not sensitive enough. Another issue to take care of is the distraction. From Figure 6.12, it can be seen that serving drinks (at $t = 45$) decreased the discomfort slightly for both seats. The influence of this distraction (i.e. serving drinks) to the comfort experience has been shown before (e.g. Lewis et al. (2016); Hiemstra-van Mastrigt (2015)).

It is also suggested to have a 5-minute general interview session after the user-test to record participants' overall seating experience. In our case the participants were enthusiastically talking about their experience, and they may give crucial feedback that they may have not written in the questionnaire. In addition to subjective rating and pressure mapping, in-seat movement during the user-test seems to be a promising measurement method as it is related to discomfort (Cascioli, Liu, Heusch, & McCarthy, 2016; Sammonds, Fray, & Mansfield, 2017). It is recommended to consider also recording fidgeting in future studies. Finally, dynamic testing (Federal Aviation Administration, 1989) and flammability testing (Federal Aviation Administration, 1986) should be conducted on the prototype in accordance to the regulations for their implementation in aircraft.

6.4. Conclusion

This study indicates that a seat pan design using foam spring technology can be lighter and more comfortable than conventional foam cushion materials. The prototype seat pan provides higher comfort than a conventional seat pan in the first 30 minutes and at the 60-minute mark. This experience was supported by pressure mapping as the pressure distribution of the prototype seat pan was found to be significantly closer to an ideal pressure distribution than the conventional seat pan. In addition, the prototype seat had a larger contact area and a lower average pressure, which in some literature is seen as linked to higher comfort. Furthermore, the seat pan cushion has a reduction of 20% in weight over a standard cushion.

6.5. Ethical approval

This study was approved by the Delft University of Technology Human Research Ethical Committee (hrec.tudelft.nl) on 22 November 2018 (approval no. 572), in accordance with The Helsinki Declaration (World Medical Association, 2013).

6.6. Declaration of competing interest

This study was financially supported by Vanema Storitve d.o.o., Slovenia. The sponsor advised on the design of the seat pan. The sponsor had no influence on the study design, data collection, analysis, data interpretation, writing and publication.

6.7. Acknowledgements

The authors would like to thank Vanema Storitve d.o.o. for their financial support and providing the necessary materials for prototyping and fabrication of the project. We thank RECARO Aircraft Seating GmbH & Co. KG for providing seat frames and standard cushions for comfort testing. We also want to thank Mr. B. Ribicic, Dr. Y. Song, and Mr. H. Werner for their support in the design of the seat pan. We want to thank Mr. S. Mane and Mr. B.J. Naagen for their great help and support in setting up this study. Last but not least we thank all the volunteers who were so kind to take part in this study.

6.8. References

- Ahmadpour, N., Lindgaard, G., Robert, J.M., & Pownall, B. (2014). The thematic structure of passenger comfort experience and its relationship to the context features in the aircraft cabin. *Ergonomics*, 57(6), 801-815. doi:10.1080/00140139.2014.899632
- Bartels, V.T. (2003). Thermal comfort of aeroplane seats: influence of different seat materials and the use of laboratory test methods. *Applied ergonomics*, 34(4), 393-399. doi:10.1016/S0003-6870(03)00058-9
- Bouwens, J.M.A. (2018). *Design considerations for airplane passenger comfort*. (Doctoral Dissertation), Delft University of Technology, Delft, The Netherlands. doi:doi.org/10.4233/uuid:306dd9f8-fab9-4f1f-8c1a-1a208e815c21
- Cascioli, V., Liu, Z., Heusch, A., & McCarthy, P.W. (2016). A methodology using in-chair movements as an objective measure of discomfort for the purpose of statistically distinguishing between similar seat surfaces. *Applied ergonomics*, 54, 100-109. doi:10.1016/j.apergo.2015.11.019
- Corlett, E.N., & Bishop, R. (1976). A technique for assessing postural discomfort. *Ergonomics*, 19(2), 175-182. doi:10.1080/00140137608931530
- De Looze, M.P., Kuijt-Evers, L.F., & Van Dieën, J. (2003). Sitting comfort and discomfort and the relationships with objective measures. *Ergonomics*, 46(10), 985-997. doi:10.1080/0014013031000121977
- Ebe, K., & Griffin, M.J. (2001). Factors affecting static seat cushion comfort. *Ergonomics*, 44(10), 901-921. doi:10.1080/00140130110064685
- Fang, R., Gao, J., & Xie, S. (2016). Analysis of pressure distribution between human and seat for evaluation of automotive seating comfort. Paper presented at the Proceedings of SAE-China Congress 2015: Selected Papers. doi:10.1007/978-981-287-978-3_35
- Federal Aviation Administration. (1986). *Flammability requirements for aircraft seat cushions (AC 25.853-1)*. U.S. Department of Transportation, Federal Aviation Administration. Retrieved from https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_25.853-1.pdf.
- Federal Aviation Administration. (1989). *Dynamic testing of part 23 airplane seat/restraint systems and occupant protection (AC No: 23.562-1)*. U.S. Department of Transportation, Federal Aviation Administration. Retrieved from https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_23_562-1.pdf.
- Filippone, A. (2012). *Advanced aircraft flight performance* (Vol. 34): Cambridge University Press. doi:10.1017/CBO9781139161893
- Franz, M., Kamp, I., Durt, A., Kilincsoy, Ü., Bubb, H., & Vink, P. (2011). A light weight car seat shaped by human body contour. *International Journal of Human Factors Modelling and Simulation*, 2(4), 314-326. doi:10.1504/ijhfrms.2011.045002
- Goossens, R., Teeuw, R., & Snijders, C. (2005). Sensitivity for pressure difference on the ischial tuberosity. *Ergonomics*, 48(7), 895-902. doi:10.1080/00140130500123647
- Helander, M.G., & Zhang, L. (1997). Field studies of comfort and discomfort in sitting. *Ergonomics*, 40(9), 895-915. doi:10.1080/001401397187739

- Hiemstra-van Mastrigt, S. (2015). *Comfortable passenger seats: Recommendations for design and research*. (Doctoral dissertation), Delft University of Technology, Delft, the Netherlands. Retrieved from [https://repository-tudelft-nl.tudelft.idm.oclc.org/islandora/object/uuid:eedd25e6-c625-45e9-9d32-f818aa89c19d](https://repository.tudelft.nl/tudelft.idm.oclc.org/islandora/object/uuid:eedd25e6-c625-45e9-9d32-f818aa89c19d) doi:10.4233/uuid:eedd25e6-c625-45e9-9d32-f818aa89c19d
- IATA. (2016). *IATA forecasts passenger demand to double over 20 years*. Montreal, Canada: International Air Transport Association. Retrieved from iata.org/pressroom/pr/Pages/2016-10-18-02.aspx.
- Lewis, L., Patel, H., Cobb, S., D'cruz, M., Bues, M., Stefani, O., & Grobler, T. (2016). Distracting people from sources of discomfort in a simulated aircraft environment. *WORK*, 54(4), 963-979. doi:10.3233/WOR-162356
- Maurice, L., Lee, D., Wuebbles, D., Isaksen, I., Finegold, L., Vallet, M., . . . Spengler, J. (2009). Assessing Current Scientific Knowledge, Uncertainties and Gaps in Quantifying Climate Change, Noise and Air Quality Aviation Impacts, final report of the International Civil Aviation Organization (ICAO) Committee on Aviation and Environmental Protection (CAEP) Workshop. Washington DC and Manchester: US Federal Aviation Administration and Manchester Metropolitan University. Retrieved from <https://www.icao.int/environmental-protection/Documents/CaepImpactReport.pdf>.
- Mergl, C. (2006). *Entwicklung eines Verfahrens zur Objektivierung des Sitzkomforts auf Automobilsitzen*. (Doctoral dissertation), Technische Universität München, München, Germany. Retrieved from <https://d-nb.info/980332915/34>
- Molenbroek, J.F.M., Jürgens, H., Houtkamp, J.J., Burger, A.K.C., Steenbekkers, L.P.A., Dirken, J.M., . . . Huysmans, T. (1984-2020). *DINED Anthropometric Database*. gdvv1984, delstu1986, kima1993, geron1998, CAESAR, Goto (2011) Children's Heads, delstu2016, chile2016-workers. Retrieved from: <https://dined.io.tudelft.nl/>
- Ordoukhanian, E., & Madni, A.M. (2014). Blended wing body architecting and design: current status and future prospects. *Procedia Computer Science*, 28, 619-625. doi:10.1016/j.procs.2014.03.075
- Poppe, W. (1980). Washington, United States of America Patent No. US4194255A. U.S. Patent and Trademark Office.
- Sammonds, G.M., Fray, M., & Mansfield, N.J. (2017). Effect of long term driving on driver discomfort and its relationship with seat fidgets and movements (SFMs). *Applied ergonomics*, 58, 119-127.
- Schäfer, A.W., Evans, A.D., Reynolds, T.G., & Dray, L. (2016). Costs of mitigating CO2 emissions from passenger aircraft. *Nature Climate Change*, 6(4), 412-417. doi:10.1038/NCLIMATE2865
- Smulders, M., Berghman, K., Koenraads, M., Kane, J., Krishna, K., Carter, T., & Schultheis, U. (2016). Comfort and pressure distribution in a human contour shaped aircraft seat (developed with 3D scans of the human body). *WORK*, 54(4), 925-940.

- Space, D.R., Johnson, R.A., Rankin, W.L., & Nagda, N.L. (2000). The airplane cabin environment: past, present and future research. In N. Nagda (Ed.), *Air quality and comfort in airliner cabins* (pp. 189-214): ASTM International. doi:10.1520/STP14495S
- Van der Grinten, M.P., & Smitt, P. (1992). Development of a practical method for measuring body part discomfort. *Advances in industrial ergonomics and safety*, 4(635), 311-318.
- Vink, P., Bazley, C., Kamp, I., & Blok, M. (2012). Possibilities to improve the aircraft interior comfort experience. *Applied ergonomics*, 43(2), 354-359. doi:10.1016/j.apergo.2011.06.011
- Vink, P., & Brauer, K. (2011). *Aircraft Interior Comfort and Design*. Boca Raton, FL, USA: CRC Press. doi:10.1201/b10815
- Vink, P., & Lips, D. (2017). Sensitivity of the human back and buttocks: The missing link in comfort seat design. *Applied ergonomics*, 58, 287-292. doi:10.1016/j.apergo.2016.07.004
- Wang, X., Cardoso, M., & Beurier, G. (2018). Effects of seat parameters and sitters' anthropometric dimensions on seat profile and optimal compressed seat pan surface. *Applied ergonomics*, 73, 13-21. doi:10.1016/j.apergo.2018.05.015
- Wang, X., Pu, Q., & Liu, H. (2014). Study on the relationship between sitting time tolerance and body pressure distribution. Paper presented at the Proceedings of the 13th International Conference on Man-Machine-Environment System Engineering, Berlin, Heidelberg. doi:10.1007/978-3-642-38968-9_12
- Zemp, R., Taylor, W.R., & Lorenzetti, S. (2015). Are pressure measurements effective in the assessment of office chair comfort/discomfort? A review. *Applied ergonomics*, 48, 273-282. doi:10.1016/j.apergo.2014.12.010
- Zenk, R. (2008). *Objektivierung des Sitzkomforts und seine automatische Anpassung*. (Doctoral dissertation), Technische Universität München, München, Germany. Retrieved from <https://mediatum.ub.tum.de/doc/656298/>
- Zenk, R., Mergl, C., Hartung, J., Sabbah, O., & Bubb, H. (2006). *Objectifying the comfort of car seats* (0148-7191). Retrieved from

DESIGN FOR ENTERTAINMENT AND RECLINED SLEEP IN TRANSIT

Part 4 discusses head-neck support and head pressure sensitivity, which can be used to design headrests to facilitate watching IFE/IVE and reclined sleep. Chapter 9 discusses how head-neck support could benefit watching IFE in a common slouched posture. Such head support could also be beneficial to reclined sleep. Chapter 10 discusses the development of a head, face and neck pressure discomfort threshold model, which could be used to make choices in cushioning firmness of zones in a headrest interfacing with the body for comfortable head support in watching IFE or reclined sleeping support (Smulders, 2018). Such a model is not only limited to the application in seat and bed design, but can also be used in other applications, such as headsets, helmets, face masks, glasses and goggles, and much more.

SLEEPING POSTURES IN ADULTS

A LITERATURE EXPLORATION

This chapter has been published as:

Smulders, M. (2018). Flex and relax: an exploration on headrest design for sleeping and watching IFE in premium aircraft seats. (Master thesis) Delft University of Technology, Delft, The Netherlands.

Smulders, M., & Vink, P. (2022). Sleeping postures in adults: a literature review. In 21st *Triennial Congress of the International Ergonomics Association*, Vancouver, Canada.

ABSTRACT

During healthy sleep, humans change their posture 20-40 times and conduct additional (micro)movements. When designing sleeping systems for at home contexts, medical contexts and limited spaces in vehicles, knowledge on (dominant) sleeping postures is essential in order to enable humans to assume these postures and to provide room for postural changes.

Literature shows that healthy adults predominantly sleep in a lateral position (39-73%), and to lesser extent in a supine (11-55%) and a prone (5-21%) position. Although detailed information on limb orientation and movement is limited in literature, this indicates that lateral and supine sleeping postures need to be facilitated, with room to move the arms below the shoulders and room for leg movement. When rotating from supine to lateral (or vice versa), room is needed to turn the feet (without the need of pulling the legs up).

7.1. Introduction

In designing sleeping systems for at home (e.g. beds and sleeping sofas), clinical (e.g. hospital beds, insomnia-, decubitus- and apnoea prevention) and in transit contexts where space is scarce (e.g. aircraft-, crew-, autonomous car- and long-distance bus seats, crew bunks in aircraft, ships, submarines and trains), knowledge on sleeping postures and movement is essential in order to provide a comfortable and efficient sleeping environment.

Humans do not sleep in one static posture, but often have a preferred posture which is dominant (Coenen, 2006; Coenen & Kolff, 2011; Haex, 2004; Verhaert, Haex, De Wilde, et al., 2011). In this posture humans usually fall asleep, but they will move as healthy sleep requires several major posture changes throughout the night (Coenen, 2006; De Koninck, Lorrain, & Gagnon, 1992; Verhaert, Haex, De Wilde, et al., 2011). During an average night, a person will change posture between 20-40 times (Coenen, 2006; Coenen & Kolff, 2011; De Koninck et al., 1992; Haex, 2004; Johnson, Swan, & Weigand, 1930; Verhaert, Haex, De Wilde, et al., 2011) and make between 40-200 movements (Alihanka & Vaahtoranta, 1979; Verhaert, Haex, De Wilde, et al., 2011). These postural changes, together with limb movements, are of importance to prevent pressure sores (Defloor, 2000; Rithalia, 2005), muscle stiffness (Haex, 2004) and enable proper blood flow (Defloor, 2000). It is thus important that a sleeping facility provides enough space and support to allow for natural occurring postural change and movement.

Information on sleeping postures and movement can help designers, engineers, ergonomists, and physicians to design better sleeping environments, which allow for natural occurring and essential in sleep (micro)movements and postural changes. As no peer-reviewed article has been published with a sole focus on sleeping postures and/or movement, this literature exploration aims to review, compare and evaluate existing literature containing data on sleeping postures and movement in healthy adults. This can give an indication on dominance/preference of certain postures in healthy adults as input for defining sleep space and support.

7.2. Method

Studies for this literature review were retrieved from Scopus, PubMed and Google Scholar, by using the following search terms: *'sleep'* and/or *'sleeping'*, and/or *'posture'*, *'position'*, *'body'*, *'orientation'*, and/or *'lying'*, and/or *'supine'*, *'back'*, *'dorsal'*, *'lateral'*, *'side'* and/or *'prone'*, and/or *'movement'* and/or *'motility'*. The following terms were excluded from the search: *'disorder'*, *'animal'*, *'apnoea'*, *'obesity'* and *'drugs'*. Additionally, filters were used to only include results published in English, and published between 1970 and 2018. From this set, only original experimental peer-reviewed studies, questionnaires with empirical data, peer-reviewed literature reviews, or books were selected, which:

- Investigate full-flat (180°; no reclined, upright or zero-gravity) single sleep (no bed partner) in healthy adults (18-65y; no infants, children or elderly);

- Describe postures at minimum in terms of lateral, supine and prone, or in more detail; or describes movement;
- Allowed participants to freely choose their postures (thus excluding experiments with predetermined postures);
- Provide the amount of participants and describes the method.

This search resulted in a limited amount of papers which focussed on sleep posture observations. Therefore, additional papers were searched by following reference threads from the selected articles, articles referring to the selected articles and similar articles (through ‘*similar articles*’ option). Papers on sleep, with no specific focus on posture, were also screened on containing information on sleeping postures.

7.3. Results

Literature that matched the selection criteria can be found in Table 7.1. In the literature, three main postures are defined: lateral, supine and prone. Within these three, there are many variations (e.g. limb orientation), but these variations are not widely studied. Seven studies differentiate between lateral left and right. Only De Koninck, Gagnon, and Lallier (1983) and De Koninck et al. (1992) describe the position of the head, trunk, legs and arms in more detail.

Literature indicates that lateral and supine sleeping postures are dominant, with roughly 55-70% lateral, 20-30% supine and 5-10% prone. Video analysis based studies of De Koninck et al. (1983), De Koninck et al. (1992), Gordon, Grimmer, and Trott (2004), Gordon and Buettner (2009), Verhaert, Haex, Wilde, et al. (2011) and Roach, Matthews, Naweed, Kontou, and Sargent (2018) found sleeping postures ranging between 51.3-73.0% for lateral, 20.1-32.2% for supine and 6.3-20.6% for prone. Sensor based studies of Sahlin, Franklin, Stenlund, and Lindberg (2009), Coenen and Kolff (2011), Verhaert, Haex, De Wilde, et al. (2011) and Skarpsno, Mork, Nilsen, and Holtermann (2017) found 39.1-56.2% for lateral, 30.2-55.3% for supine and 5.6-13.6% for prone. The survey based study on self-reported sleeping postures of Gordon, Grimmer, and Trott (2007) reports for lateral 72%, supine 11% and prone 5%.

De Koninck et al. (1983) found that the head is kept predominantly lateral (36% left, 45% right) or upward (16%), arms are both kept predominantly below the shoulder (78%) of which 61% is in a folded position, where there is more variation in the legs: 43% both folded, 30% one folded and one straight, and 27% both straight. Very similar values were found in the follow-up study by De Koninck et al. (1992) in the age group 18-45y.

Table 7.1 | Sleeping postures in healthy adults, expressed as percentage of Total Bed Time (TBT), Total Sleep Time (TST) or total amount of respondents (n). TBT is the total amount of time that a person spends in bed, regardless of whether they are sleeping during that time. TST is the amount of time spent sleeping and is the sum of all REM and NREM sleep in a sleep episode.

Source	Method	Sample size	Measure	Lateral		Supine	Prone
				Left	Right		
De Koninck et al. (1983)	Video analysis (incl. PSG)	n = 8	% of TBT ¹	30% ²	33% ²	23% ²	14% ²
De Koninck et al. (1992)	Video analysis (incl. PSG)	n = 20 ³	% of TBT ¹	30.7 ±10.9%	33.8 ±12.2%	20.1 ±12.8%	15.2 ±16.0%
Gordon et al. (2004)	Video analysis	n = 12	% of TBT	73.2 ±18.0% ⁴		20.5 ±14.6% ⁴	6.3 ±8.0% ⁴
Gordon and Buettner (2009)	Video analysis	n = 12 ⁵	% of TST	42.1 ±18.0%	29.8 ±20.4%	21.7 ±13.0%	6.4 ±7.4%
Verhaert, Haex, Wilde, et al. (2011)	Video analysis	n = 17	% of TBT ¹	55.4 ±17.3%		32.2 ±19.2%	12.4 ±13.7%
Roach et al. (2018)	Video analysis (incl. PSG)	n = 6	% of TST	24.8 ±15.7%	26.5 ±18.6%	28.0 ±29.0%	20.6 ±32.4%
Sahlin et al. (2009)	Body position sensor (PSG)	n = 399 ⁶	% of TBT ¹	24%	27%	41%	9%
Coenen and Kolff (2011)	Body position sensor	n = 28 ⁵	% of TST	21.8 ±26.2%	17.3 ±21.1%	55.3 ±15.8%	5.6% ⁷
Verhaert, Haex, De Wilde, et al. (2011)	Pressure sensor	n = 15	% of TBT	30.2 ±16.8%	26.0 ±17.2%	30.2 ±20.5%	13.6 ±16.4%
Skarpsno et al. (2017)	Accelerometer	n = 664	% of TBT	54.1 ±18.1%		37.5 ±18.2%	7.3 ±12.3%
Gordon et al. (2007)	Self-reported dominant posture	n = 812	% of n	72% ⁸		11% ⁸	5% ⁸

¹ Publication is not very clear on the defined start and end points, stating % of time spent per night or % time spent. Most obvious measure used would be Total Bed Time (TBT); the time spent in bed during the experiment.

² Based on the trunk position.

³ Age groups 18-24y and 35-45y are combined.

⁴ Based on reanalysis of dataset from table 1 in Gordon et al. (2004), as table 2 in Gordon et al. (2004) contains mistakes. Remaining percentage is 'other'.

⁵ All age groups (18-60+ years).

⁶ General population sample of women only, consisting of both healthy and unhealthy participants, between 20-70y.

⁷ Calculated percentage, as it is not given by Coenen and Kolff (2011).

⁸ Males and females are combined. Remaining percentage is "other" (not shown).

7.4. Discussion

Although this selection of literature gives a good indication of dominant sleeping postures, most studies do not predominantly focus on sleeping postures themselves. Ten studies captured postures (e.g. by video or sensor) and one study was based solely on questionnaires. Although survey based dominant posture acquisition can be considered as limited, a strong correlation has been found between reported and actual taken postures (Gordon et al., 2004; Kaplowitz et al., 2015; Verhaert, Haex, De Wilde, et al., 2011). Participants undergoing polysomnography (PSG) in the aforementioned studies may have felt constrained by the PSG leads and other equipment attached to their body. This limitation may thereby have influenced the study results. Metersky and Castriotta (1996) showed that the time spent supine was 56% greater during the PSG night than the non-PSG nights.

In the literature, supine and lateral sleeping are generally considered as the “best” positions (Coenen, 2006; Haex, 2004), as in a prone sleeping posture the body puts pressure on vital organs, the lumbar area of the spine will be curved and the head will be sideways in respect to the body (Coenen, 2006). Except in a full-flat bed (e.g. a premium business or first class seat), prone sleeping in a reclined seat is unpractical or impossible. The studies indicate no clear preference between left or right lateral sleeping. However, Sahlin (2008) found that obese women spend significantly more time on their right side. Although there is no difference in loading on the body for left or right side sleeping, when sleeping on the left side the weight of the liver works on the lungs and stomach (Haex, 2005).

Coenen and Kolff (2011), Verhaert, Haex, De Wilde, et al. (2011) and De Koninck et al. (1992) found large intra- and inter-individual variations, where sleepers show a large variation in postures and variation in time spent in these varied postures. Literature also suggests that limiting sleep to one side is not advisable, as movement in sleep is natural and essential to prevent pressure sores (Defloor, 2000; Rithalia, 2005), muscle stiffness (Haex, 2004) and to enable proper blood flow (Defloor, 2000). Thus, when designing for sleep, posture variation should be facilitated, and predominantly lateral and supine postures.

The majority of studies consider only three (lateral, supine and prone) or four (with the distinction between lateral left and right) postures, where variations based on limb orientation would give more precise results within these major categories. Although the two studies by De Koninck and colleagues (1983; 1992) give more postural detail, their descriptions are still generic. For defining the ideal sleep envelope at home and a minimal sleep envelope for transportation, detailed posture and movement information is still lacking.

More detailed research is thus needed on sleeping postures and movement, including the orientation of limbs, and movement (macro- and micro movements) during in-bed time and sleep, in order to define a better sleeping environment.

7.5. Conclusion

During healthy sleep, humans change their posture 20-40 times and conduct additional (micro)movements. When designing beds and seats for sleeping, it is thus important to provide ample room for postural changes. Literature indicates that lateral and supine sleeping postures are dominant, with roughly 39-73% lateral, 11-55% supine and 5-21% prone (see Figure 7.1). Although detailed information on limb orientation and movement is limited in literature, this indicates that lateral and supine sleeping postures need to be facilitated, with room to move the arms below the shoulders and room for leg movement. When rotating from supine to lateral (or vice versa), room is needed to turn the feet (without the need of pulling the legs up).

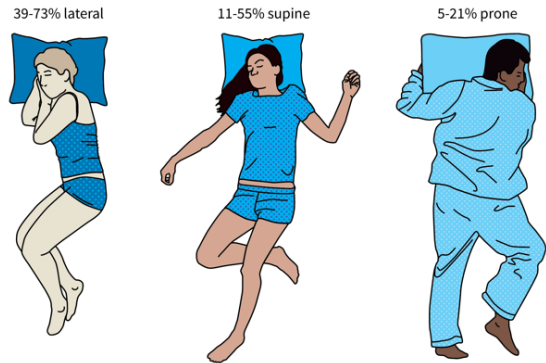


Figure 7.1 | Ranges of performed sleeping postures from literature as shown in Table 7.1.

More detailed research on sleeping postures and movement (especially limb orientation and movement) is needed. Combined with anthropometric variation within the target population, this could provide a starting point in the design of a minimal space envelope which provides sufficient space for natural sleep behaviour (i.e. sufficient space for postural change and limb movement) (see Figure 7.2). However, a balance between space minimisation and sleep quality and comfort provided needs to be struck. Therefore, further research is needed on the influence of the (minimal) sleep space provided on postural changes, in sleep movement and their effects on sleep quality and comfort.



Figure 7.2 | Example of how postures could dictate a minimal space envelope which provides room for postural change and movement. In such a design, anthropometric variation within the target population needs to be considered.

7.6. References

- Alihanka, J., & Vahtoranta, K. (1979). A static charge sensitive bed. A new method for recording body movements during sleep. *Electroencephalography and Clinical Neurophysiology*, 46(6), 731-734. doi:10.1016/0013-4694(79)90113-5
- Coenen, A.M.L. (2006). De slaap en het bed: een psychobiologische beschouwing [Dutch]. *Medische Antropologie*, 18(1), 133-148.
- Coenen, A.M.L., & Kolff, M. (2011). Body postures in sleep. Annual Proceedings of the NSWO (Dutch Society for Sleep-Wake Research), 22, 44-47.
- De Koninck, J., Gagnon, P., & Lallier, S. (1983). Sleep positions in the young adult and their relationship with the subjective quality of sleep. *Sleep*, 6(1), 52-59. doi:10.1093/sleep/6.1.52
- De Koninck, J., Lorrain, D., & Gagnon, P. (1992). Sleep positions and position shifts in five age groups: an ontogenetic picture. *Sleep*, 15(2), 143-149. doi:10.1093/sleep/15.2.143
- Defloor, T. (2000). The effect of position and mattress on interface pressure. *Applied nursing research*, 13(1), 2-11. doi:10.1016/S0897-1897(00)80013-0
- Gordon, S.J., & Buettner, P.G. (2009). Age and lateral sleep position: a pilot study. *Internet Journal of Allied Health Sciences and Practice*, 7(1), 13. doi:10.46743/1540-580X/2009.1232
- Gordon, S.J., Grimmer, K.A., & Trott, P. (2004). Self-reported versus recorded sleep position: an observational study. *Internet Journal of Allied Health Sciences and Practice*, 2(1), 7. doi:10.46743/1540-580X/2004.1034
- Gordon, S.J., Grimmer, K.A., & Trott, P. (2007). Understanding sleep quality and waking cervico-thoracic symptoms. *Internet Journal of Allied Health Sciences and Practice*, 5, 1-12. doi:10.46743/1540-580X/2007.1152
- Haex, B. (2004). Back and bed: ergonomic aspects of sleeping. Boca Raton, FL, USA: CRC press. doi:10.1201/9780203022306
- Johnson, H.M., Swan, T., & Weigand, G. (1930). In what positions do healthy people sleep? *Journal of the American Medical Association*, 94(26), 2058-2062. doi:10.1001/jama.1930.02710520024006
- Kaplowitz, K., Blizzard, S., Blizzard, D.J., Nwogu, E., Hamill, C.E., Weinreb, R.N., . . . Loewen, N.A. (2015). Time spent in lateral sleep position and asymmetry in glaucoma. *Investigative Ophthalmology & Visual Science*, 56(6), 3869-3874. doi:10.1167/iovs.14-16079
- Metersky, M.L., & Castriotta, R.J. (1996). The effect of polysomnography on sleep position: possible implications on the diagnosis of positional obstructive sleep apnea. *Respiration*, 63(5), 283-287.
- Rithalia, S. (2005). Assessment of patient support surfaces: principle, practice and limitations. *Journal of Medical Engineering & Technology*, 29(4), 163-169. doi:10.1080/03091900410001731191

- Roach, G.D., Matthews, R., Naweed, A., Kontou, T.G., & Sargent, C. (2018). Flat-out napping: The quantity and quality of sleep obtained in a seat during the daytime increase as the angle of recline of the seat increases. *Chronobiology international*, 35(6), 872-883. doi:10.1080/07420528.2018.1466801
- Sahlin, C., Franklin, K.A., Stenlund, H., & Lindberg, E. (2009). Sleep in women: normal values for sleep stages and position and the effect of age, obesity, sleep apnea, smoking, alcohol and hypertension. *Sleep medicine*, 10(9), 1025-1030. doi:10.1016/j.sleep.2008.12.008
- Skarpsno, E.S., Mork, P.J., Nilsen, T.I.L., & Holtermann, A. (2017). Sleep positions and nocturnal body movements based on free-living accelerometer recordings: association with demographics, lifestyle, and insomnia symptoms. *Nature and science of sleep*, 267-275. doi:10.2147/NSS.S145777
- Verhaert, V., Haex, B., De Wilde, T., Berckmans, D., Vandekerckhove, M., Verbraecken, J., & Vander Sloten, J. (2011). Unobtrusive assessment of motor patterns during sleep based on mattress indentation measurements. *IEEE Transactions on Information Technology in Biomedicine*, 15(5), 787-794. doi:10.1109/TITB.2011.2131670
- Verhaert, V., Haex, B., Wilde, T.D., Berckmans, D., Verbraecken, J., Valck, E.d., & Sloten, J.V. (2011). Ergonomics in bed design: the effect of spinal alignment on sleep parameters. *Ergonomics*, 54(2), 169-178.

SLEEP QUALITY AND (DIS)COMFORT IN A MINIMAL SPACE ENVELOPE

This chapter has been published as:

Smulders, M., & Vink, P. (2021). Sleep quality and (dis) comfort in minimal space envelope. In *3rd International Comfort Congress 2021*, Delft, The Netherlands.

ABSTRACT

Sleep facilities in vehicles often have a limited space due to economic and/or operational reasons. Currently, no guidelines exist on minimal sleep space envelopes for qualitative, effective and comfortable sleep. This study aims to investigate the influence of a 2D minimal space envelope on sleep quality, sleep effectiveness and (dis)comfort, in order to work towards such guidelines. Forty-one participants 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 designed by the participant. Night 2 was rated significantly least comfortable and most uncomfortable, where night 1 in the own bed was rated as most comfortable and least uncomfortable. Sleep quality and sleep effectiveness were rated worst in the limited space (night 2), which had a 30% space reduction relative to an average one-person bed (190 x 90 cm). However no significant difference in sleep quality and sleep effectiveness between the own bed (night 1) and the minimal space designed by the participant (night 3) were found, although space on average was reduced by 25%. This indicates that tweaking the dimensions of the reduced sleep space envelope can increase sleep quality, sleep effectiveness and comfort. Further research on minimal space envelope design (non-rectangular and 3D) and its influence on sleep quality and efficiency, and (dis)comfort is needed, in which sleep behaviour, sleeping postures and movement, and anthropometrics should also be taken into account.

8.1. Introduction

Sleep facilities in aircraft, trains, busses, ships, submarines, (autonomous) cars, and other vehicles often have a limited space due to economic and/or operational reasons (Smulders, 2018; Stanglmeier et al., 2020). Providing an effective and comfortable sleep is important for passenger satisfaction (Kluge, Ringbeck, & Spinler, 2020) – also to justify surplus prices (Hugon-Duprat & O'Connell, 2015; Kuo & Jou, 2017) – and crew effectiveness and operational safety – e.g. in operational safety critical environments such as aircraft cabin crews (Avers, King, Nesthus, Thomas, & Banks, 2009; Drury, Ferguson, & Thomas, 2012; Hartzler, 2014), medical staff (Dorrian et al., 2008; Gold et al., 1992; Weinger & Ancoli-Israel, 2002), offshore and maritime workers (Hope, Øverland, Brun, & Matthiesen, 2010; Hystad, Nielsen, & Eid, 2017; Sneddon, Mearns, & Flin, 2013) and military personnel (Good, Brager, Capaldi, & Mysliwiec, 2020; Grandou, Wallace, Fullagar, Duffield, & Burley, 2019; Parker & Parker, 2017). There are minimal standards for sleep facilities in safety critical environments such as aircraft (Federal Aviation Administration, 2012; Simons & Spencer, 2007), but no guidelines exist on minimal sleep space envelopes in relation to sleep quality and comfort. Such guidelines could help designers and engineers to design qualitative, effective, comfortable and compact sleep facilities. This study aims to investigate the influence of a 2D minimal space envelope on sleep quality, sleep efficiency and (dis)comfort, in order to work towards such guidelines.

8.2. Method

Forty-one participants (see Table 8.1) who were students participating in a course and did not receive compensation, took part in this study. Only data was used of students who voluntarily shared their data for this study. The participants were asked to score the experienced sleep quality (by means of the Pittsburgh Sleep Quality Index (PSQI) (Buysse, Reynolds III, Monk, Berman, & Kupfer, 1989)), sleep effectiveness (by means of the Karolinska Sleepiness Scale (KSS) (Åkerstedt & Gillberg, 1990; Kaida et al., 2006), the Samn-Perelli 7-point Fatigue Scale (SPFS) (Samn & Perelli, 1982) and a Rested Scale) and (dis)comfort after a night of sleep in three conditions (all of which were situated in the participant's own home): night 1) in their normal bed space (the bed they sleep in in their house, which was usually between 190-200 cm long and between 90-140 cm wide) (see Figure 8.1), night 2) in a limited space (170 x 70 cm) (see Figure 8.2), and night 3) in a minimal space designed by the participant (a bed space which is limited, but still rather comfortable, based on own insight and their experiences from nights 1 and 2) (see Figure 8.3). The limited sleeping space for night 2 and night 3 was obtained by means of placing boxes filled with heavy items like books. Night 1-3 were all consecutive nights.

The Wilcoxon test ($p \leq .05$) for paired samples was used to test for significance in PSQI, KSS, SPFS and (dis)comfort. The measurements of the designed minimal 2D space envelopes are combined into one average square minimal space envelope.

Table 8.1 | Participant demographics (n=41).

		Mean	SD
Male (n=12)	Age [years]	22.8	1.7
	Stature [cm]	1.85	0.07
	Weight [Kg]	75.0	7.6
Female (n=29)	Age [years]	22.9	1.6
	Stature [cm]	1.72	0.07
	Weight [Kg]	62.1	8.5

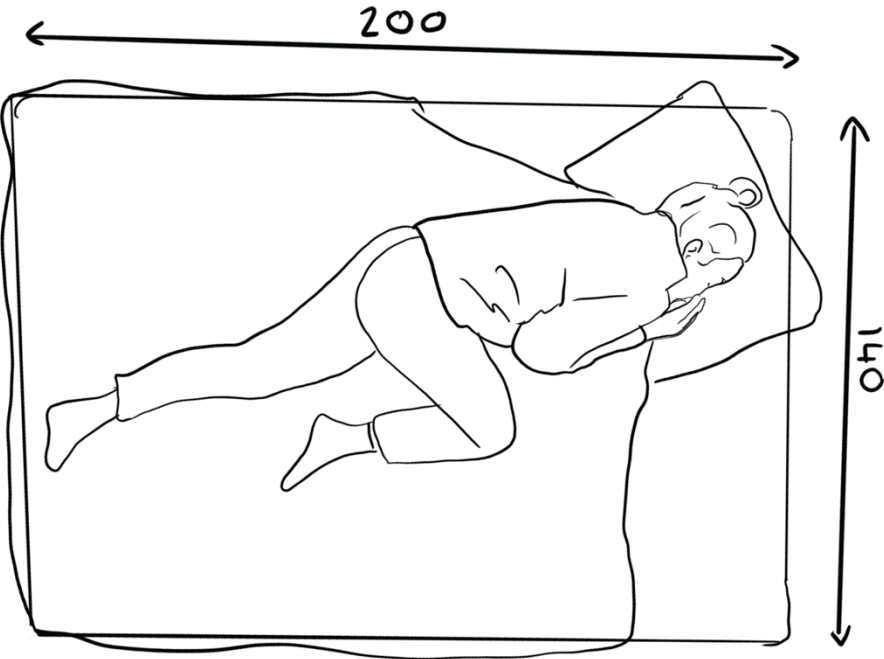


Figure 8.1 | Example of night 1: in their normal bed space.

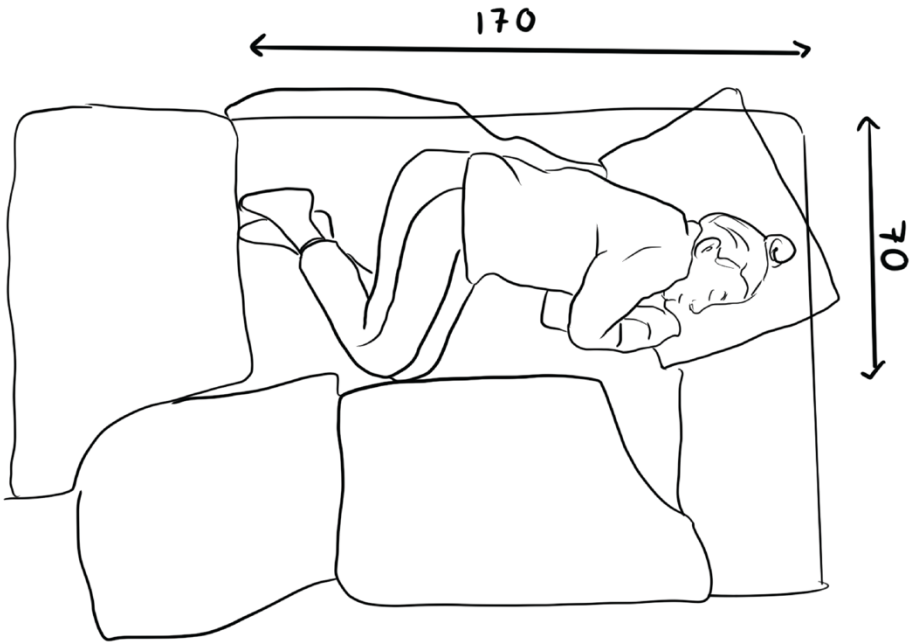


Figure 8.2 | Example of night 2: in a limited space of 170 x 70 cm.

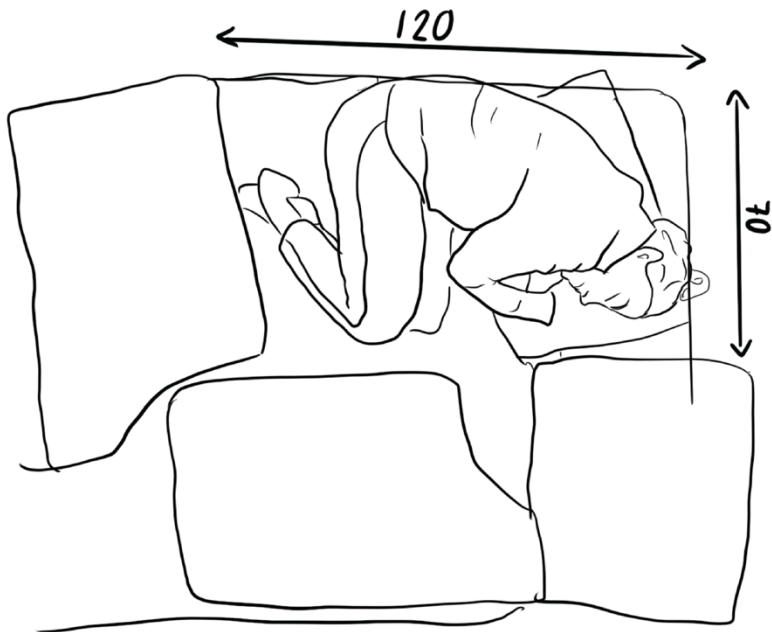


Figure 8.3 | Example of night 3: in a minimal space designed by the participant.

8.3. Results

The average comfort and discomfort scores differed significantly ($p < .01$) (see Figure 8.4). In their normal bed space (night 1) the comfort score was 3.96 (scale 1-5; 5 = maximum comfort; $SD = .73$), in a limited space (night 2) 2.59 ($SD = .91$) and in their own minimal designed sleep space (night 3) 3.0 ($SD = .90$). In their normal bed space (night 1) the discomfort was 1.53 (scale 1-5; 5 = maximum discomfort; $SD = .60$), in the limited space (night 2) 2.98 ($SD = .86$) and in their own minimal designed sleep space (night 3) 2.4 ($SD = .90$).

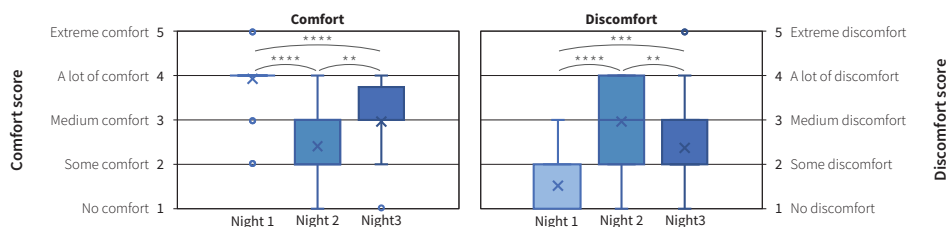


Figure 8.4 | Distribution of comfort and discomfort scores per night ($n=41$). Higher comfort and lower discomfort scores are considered better. Significant difference is stated as follows: $** = p \leq .01$, $*** = p \leq .001$, $**** = p \leq .0001$.

The minimal sleep space designed by the participants varied a lot: the minimal width was 46 cm and the maximum width was 140 cm, and the length varied from 100 to 200 cm. The mean designed sleep space was 166 x 78 cm; a reduction of 25% compared to an average one person bed (190 x 90 cm) (see Figure 8.5).

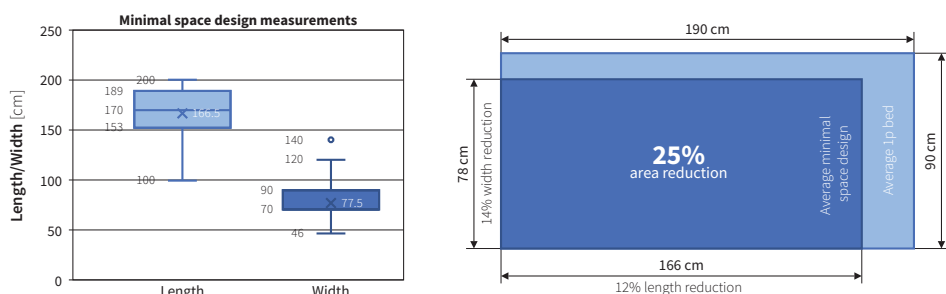


Figure 8.5 | Distribution of minimal space design measurements by the participants for night 3 and a visualisation of the 2D space area reduction from average one person bed (190 x 90 cm) to average minimal bed design by participants (166 x 78 cm) ($n=41$).

When looking at the impact on sleep quality, night 2 in the limited bed was scored worse on the PSQI score (see Figure 8.6), the Karolinska Sleepiness Scale (see Figure 8.7), the Samn-Perelli Fatigue Scale (see Figure 8.8), and the Rested Scale (see Figure 8.9) by participants than sleeping in their own bed (night 1) or their own designed sleep space (night 3). No significant difference was found in sleep quality (PSQI) between night 1 and 3. No significant difference in alertness-sleepiness (KSS) was found between

pre- and post-night for night 2, where for night 1 and 3 post-night alertness was significantly higher than pre-night. Fatigue (SPFS) significantly differed for all nights between pre- and post-night. Participants felt significant more rested post-night 1 and 3 compared to night 2, where no significant difference was found between night 1 and 3.

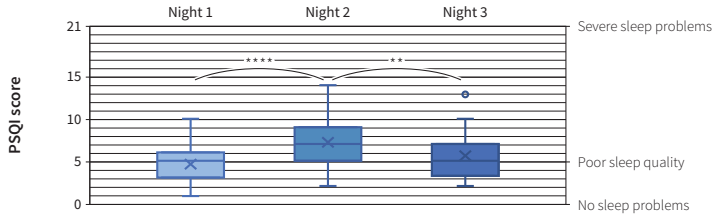


Figure 8.6 | Distribution of PSQI scores per night (n=41). Higher PSQI scores are considered better. Significant difference is stated as follows: * = $p \leq .05$, ** = $p \leq .01$, **** = $p \leq .0001$.

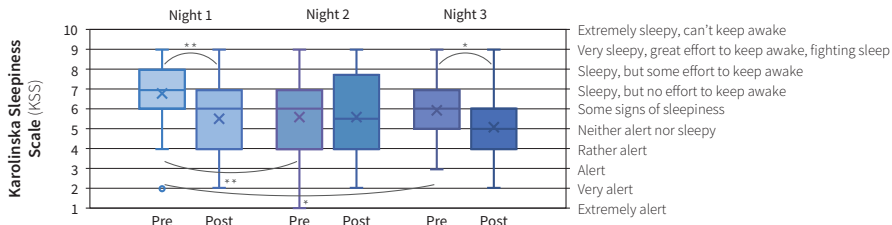


Figure 8.7 | Distribution of KSS alertness/sleepiness scores per pre- and post-night (n=41). Lower post- than pre-night KSS scores are considered better. Significant difference is stated as follows: * = $p \leq .05$, ** = $p \leq .01$.

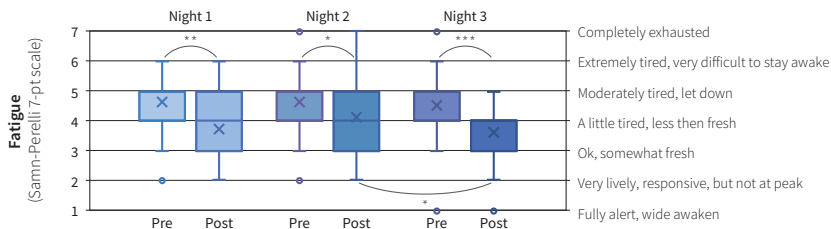


Figure 8.8 | Distribution of SPFS scores per pre- and post- night (n=41). Lower post- than pre-night fatigue scores are considered better. Significant difference is stated as follows: * = $p \leq .05$, ** = $p \leq .01$, *** = $p \leq .001$.

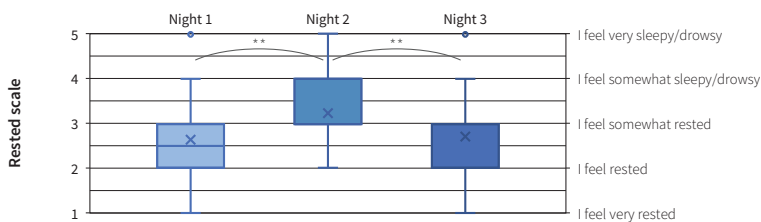


Figure 8.9 | Distribution of rested after night scores per night (n=41). Lower scores are considered better. Significant difference is stated as follows: ** = $p \leq .01$.

8.4. Discussion

This study shows that reducing the sleep space envelope influences (dis)comfort, sleep quality and sleep effectiveness. Participants were able to sleep in all three conditions, but sleep quality (PSQI), sleep effectiveness (KSS, SPFS and Rested scales) and comfort were rated lowest, and discomfort rated highest in the limited space of 170 x 70 cm (night 2). The lack of significant difference in alertness-sleepiness (KSS) between pre- and post-night 2, and the significantly higher post-night fatigue (SPFS) and significantly worse “rested” score for night 2 compared to night 3 indicate a limited recovery and thus limited effectiveness of the night 2 sleep. The minimal space designed by the participants (night 3) also showed significant lower comfort and significant increased discomfort than the own bed (night 1) (although to a significant lesser extent than night 2), but the sleeping quality (PSQI) and sleep effectiveness (KSS, SPFS and Rested scale) scores were not significantly different between night 1 and 3, despite the space envelope reduction. What stands out is the minor difference in space envelope reduction between night 2 and 3 (30% versus 25% reduction compared to an average one-person bed of 190 x 90 cm), while night 3 scored significant better on (dis)comfort, sleep quality (PSQI) and sleep effectiveness (SPFS and Rested scales) than night 2. This makes the space reduction in the average minimal space designed by the participants of 166 x 78 cm for night 3 possibly more acceptable for the benefit of space reduction while limiting the negative impact on comfort, sleep quality and sleep efficiency. These results also show that tweaking the dimensions can significantly improve the comfort, sleep quality and sleep effectiveness with still a quite similar reduction in space envelope.

This study was conducted with a limited population size ($n=41$) and limited variation in age (range of 20-28y). As older age groups have different sleep behaviour than younger age groups (De Koninck, Lorrain, & Gagnon, 1992; Luca et al., 2015), generalising the data of this study should be done with care. As more females than males participated in the course, the population gender sample for this study was unbalanced. In future research, older populations should also be included, and a better gender balance should be sought. This study was also limited as only 2D rectangular spaces were used, whereas non-rectangular and 3D shaped spaces could have resulted in more space reduction (e.g. combining multiple beds next to each other with non-rectangular spaces and/or stacking on top of each other could create possibilities to have more passengers sleep comfortably in a minimal space envelope) with the same comfort and sleep quality. Different minimal sleep space designs, movement patterns during sleep and anthropometrics, and their relation to sleep quality and (dis)comfort need to be investigated further.

There could be an order influence, as the conditions were sequential, but this was on purpose: by experiencing the reduced space (night 2) compared to their normal bed (night 1), participants were made aware of the consequences of space reduction in both length and width, allowing them to make a motivated redesign based on their own experience for night 3. However, as night 2 generally resulted in a reduced recovery, it could have influenced the PSQI, KSS, Samn-Perelli 7-pt fatigue scale and rested scores of night 2 and sequential night 3. This study is also only based on subjective data, as sleep quality was self-reported. Further research might include objective polysomnography (PSG) to measure sleep quality and sleep efficiency.

8.5. Conclusion

Sleeping in a limited space is possible (as shown in this experiment), however the quality of sleep and comfort are significantly lower and discomfort significantly higher in the limited space (170 x 70 cm). Tweaking the 2D dimensions of the reduced space can limit the negative impact on sleep quality and (dis)comfort.

Further research on minimal space envelope design (non-rectangular and 3D) and its influence on sleep quality and efficiency (preferably with PSG), and comfort are needed, where also sleep behaviour (Smulders and Vink (2021); see Chapter 2), sleeping postures and movement (see Chapter 7), and anthropometrics should be taken into account.

8.6. Ethical approval

This study was approved by the Delft University of Technology Human Research Ethical Committee (hrec.tudelft.nl) on 12 November 2021 (approval no. 1833), in accordance with The Helsinki Declaration (World Medical Association, 2013).

8.7. References

- Åkerstedt, T., & Gillberg, M. (1990). Subjective and objective sleepiness in the active individual. *International Journal of Neuroscience*, 52(1-2), 29-37. doi:10.3109/00207459008994241
- Avers, K.B., King, S.J., Nesthus, T.E., Thomas, S., & Banks, J. (2009). *Flight Attendant Fatigue, Part 1: National Duty, Rest, and Fatigue Survey*. (DOT/FAA/AM-09/24). Oklahoma City: Civil Aerospace Medical Institute, Federal Aviation Administration. Retrieved from <https://apps.dtic.mil/sti/pdfs/ADA520848.pdf>.
- Buysse, D.J., Reynolds III, C.F., Monk, T.H., Berman, S.R., & Kupfer, D.J. (1989). The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. *Psychiatry research*, 28(2), 193-213. doi:10.1016/0165-1781(89)90047-4
- De Koninck, J., Lorrain, D., & Gagnon, P. (1992). Sleep positions and position shifts in five age groups: an ontogenetic picture. *Sleep*, 15(2), 143-149. doi:10.1093/sleep/15.2.143
- Dorrian, J., Tolley, C., Lamond, N., van den Heuvel, C., Pincombe, J., Rogers, A.E., & Drew, D. (2008). Sleep and errors in a group of Australian hospital nurses at work and during the commute. *Applied ergonomics*, 39(5), 605-613. doi:10.1016/j.apergo.2008.01.012
- Drury, D.A., Ferguson, S.A., & Thomas, M.J. (2012). Restricted sleep and negative affective states in commercial pilots during short haul operations. *Accident Analysis & Prevention*, 45, 80-84. doi:10.1016/j.aap.2011.09.031
- Federal Aviation Administration. (2012). *Flightcrew Member Rest Facilities* (AC 117-1). Federal Aviation Administration Retrieved from faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/1020336.
- Gold, D.R., Rogacz, S., Bock, N., Tosteson, T.D., Baum, T.M., Speizer, F.E., & Czeisler, C.A. (1992). Rotating shift work, sleep, and accidents related to sleepiness in hospital nurses. *American journal of public health*, 82(7), 1011-1014. doi:10.2105/ajph.82.7.1011
- Good, C.H., Brager, A.J., Capaldi, V.F., & Mysliwiec, V. (2020). Sleep in the United States military. *Neuropsychopharmacology*, 45(1), 176-191. doi:10.1038/s41386-019-0431-7
- Grandou, C., Wallace, L., Fullagar, H.H., Duffield, R., & Burley, S. (2019). The effects of sleep loss on military physical performance. *Sports Medicine*, 49(8), 1159-1172. doi:10.1007/s40279-019-01123-8
- Hartzler, B.M. (2014). Fatigue on the flight deck: the consequences of sleep loss and the benefits of napping. *Accident Analysis & Prevention*, 62, 309-318. doi:10.1016/j.aap.2013.10.010
- Hope, S., Øverland, S., Brun, W., & Matthiesen, S.B. (2010). Associations between sleep, risk and safety climate: A study of offshore personnel on the Norwegian continental shelf. *Safety Science*, 48(4), 469-477. doi:10.1016/j.ssci.2009.12.006
- Hugon-Duprat, C., & O'Connell, J.F. (2015). The rationale for implementing a premium economy class in the long haul markets—Evidence from the transatlantic market. *Journal of Air Transport Management*, 47, 11-19. doi:10.1016/j.jairtraman.2015.03.005

- Hystad, S., Nielsen, M., & Eid, J. (2017). The impact of sleep quality, fatigue and safety climate on the perceptions of accident risk among seafarers. *European review of applied psychology*, 67(5), 259-267. doi:10.1016/j.erap.2017.08.003
- Kaida, K., Takahashi, M., Åkerstedt, T., Nakata, A., Otsuka, Y., Haratani, T., & Fukasawa, K. (2006). Validation of the Karolinska sleepiness scale against performance and EEG variables. *Clinical neurophysiology*, 117(7), 1574-1581. doi:10.1016/j.clinph.2006.03.011
- Kluge, U., Ringbeck, J., & Spinler, S. (2020). Door-to-door travel in 2035–A Delphi study. *Technological Forecasting and Social Change*, 157, 120096. doi:10.1016/j.techfore.2020.120096
- Kuo, C.-W., & Jou, R.-C. (2017). Willingness to pay for airlines' premium economy class: The perspective of passengers. *Journal of Air Transport Management*, 59, 134-142. doi:10.1016/j.jairtraman.2016.12.005
- Luca, G., Haba Rubio, J., Andries, D., Tobback, N., Vollenweider, P., Waeber, G., . . . Tafti, M. (2015). Age and gender variations of sleep in subjects without sleep disorders. *Annals of medicine*, 47(6), 482-491. doi:10.3109/07853890.2015.1074271
- Parker, R.S., & Parker, P. (2017). The impact of sleep deprivation in military surgical teams: a systematic review. *BMJ Military Health*, 163(3), 158-163. doi:10.1136/jramc-2016-000640
- Samn, S.W., & Perelli, L.P. (1982). *Estimating aircrew fatigue: a technique with application to airlift operations*. (SAM-TR-82-21). Texas, USA: USAF School of Aerospace Medicine. Retrieved from <https://apps.dtic.mil/sti/pdfs/ADA125319.pdf>.
- Simons, M., & Spencer, M. (2007). *Extension of flying duty period by in-flight relief*. (TNO-DV 2007 C362). Soesterberg: TNO Defence, Security and Safety.
- Smulders, M. (2018). *Flex and relax: An exploration on headrest design for sleeping and watching IFE in premium aircraft seats*. (MSc. Thesis), Delft University of Technology, Delft. Retrieved from <http://resolver.tudelft.nl/uuid:4e929659-63d7-4816-82b0-a35cd20725ea>
- Smulders, M., & Vink, P. (2021). Human behaviour should be recorded in (dis)comfort research. *WORK*, 68(S1), S289-S294. doi:10.3233/WOR-208027
- Sneddon, A., Mearns, K., & Flin, R. (2013). Stress, fatigue, situation awareness and safety in offshore drilling crews. *Safety Science*, 56, 80-88. doi:10.1016/j.ssci.2012.05.027
- Stanglmeier, M.J., Paternoster, F.K., Paternoster, S., Bichler, R.J., Wagner, P.-O., & Schwirtz, A. (2020). Automated driving: A biomechanical approach for sleeping positions. *Applied ergonomics*, 86, 103103.
- Weinger, M.B., & Ancoli-Israel, S. (2002). Sleep deprivation and clinical performance. *Jama*, 287(8), 955-957. doi:10.1001/jama.287.8.955

DESIGN FOR ENTERTAINMENT AND RECLINED SLEEP IN TRANSIT

Part 4 discusses head-neck support and head pressure sensitivity, which can be used to design headrests to facilitate watching IFE/IVE and reclined sleep. Chapter 9 discusses how head-neck support could benefit watching IFE in a common slouched posture. Such head support could also be beneficial to reclined sleep. Chapter 10 discusses the development of a head, face and neck pressure discomfort threshold model, which could be used to make choices in cushioning firmness of zones in a headrest interfacing with the body for comfortable head support in watching IFE or reclined sleeping support (Smulders, 2018). Such a model is not only limited to the application in seat and bed design, but can also be used in other applications, such as headsets, helmets, face masks, glasses and goggles, and much more.

NECK POSTURE AND MUSCLE ACTIVITY IN A RECLINED BUSINESS CLASS AIRCRAFT SEAT WATCHING IFE WITH AND WITHOUT HEAD SUPPORT

This chapter has been published as:

Smulders, M., Naddeo, A., Cappetti, N., van Grondelle, E.D., Schultheis, U.W., & Vink, P. (2017) Neck posture and muscle activity with and without head support in a reclined sitting posture when watching IFE. In *1st International Comfort Congress* (pp. 1-10), Salerno, Italy.

Smulders, M., Naddeo, A., Cappetti, N., Van Grondelle, E. D., Schultheis, U., & Vink, P. (2019). Neck posture and muscle activity in a reclined business class aircraft seat watching IFE with and without head support. *Applied ergonomics*, 79, 25-37.

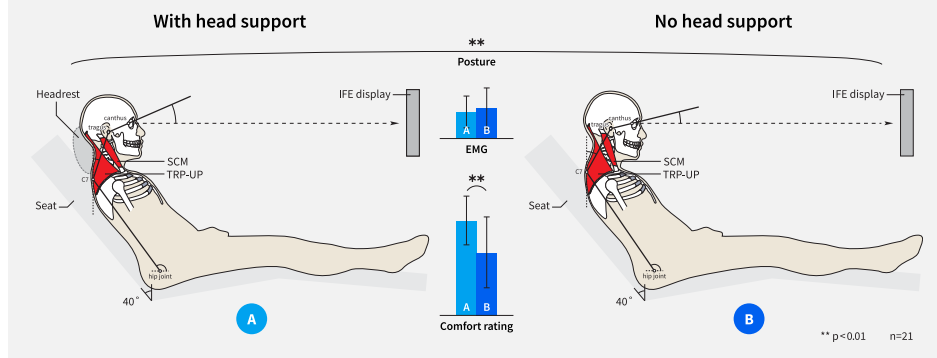
ABSTRACT

The purpose of this study is to determine if a headrest benefits the comfort of the passenger and lowers muscle activity in the neck when sitting in a reclined (slouched) posture while watching *In-Flight Entertainment* (IFE) in an aircraft business class seat.

No significant differences in muscle activity in the *musculus sternocleidomastoid* and *musculus trapezius pars descendant* were found between the conditions with headrest and without headrest. A significant difference in expected comfort rating was found. Participants indicated they expect to experience more comfort with a headrest when watching IFE for a duration of two movies during a long-haul flight. This study also found a significant difference in posture. In the condition without headrest the head was more upright compared to the condition with headrest.

The lack of significant difference in muscle activity and the significant difference in posture may indicate that humans tend to look for a head position that is neutral, in the sense of minimal muscle effort.

This study shows that the use of a headrest may benefit the comfort experience of the passenger during flight. However, further research is needed on the design of the headrest and the long-term effects of head support on comfort, discomfort, muscle activity and fatigue for watching IFE in a slouched posture.



Abbreviations

EMG (sEMG)	(surface) Electromyography: an electrodiagnostic medicine technique for evaluating and recording the electrical activity produced by skeletal muscles.
ICE/IVI	In-Car Entertainment or In-Vehicle Infotainment: a collection of hardware and software in automobiles that provides audio or video entertainment. It is to some extent comparable with IFE.
IFE	In-Flight Entertainment: the screens and related systems on board of an aircraft to entertain passengers, featuring (depending on what the airline offers) movies, (live) TV, games, interactive maps, magazines, etcetera. In economy class these screens are mainly mounted at the upper part of the backrest and for bulkhead seats mounted on an arm that can be stowed in the armrest. In business class these screens are often mounted against the shell of the seat in front or on the bulkhead. Less common is to have the display stowed in the armrest, which can be folded out.
MVC	Maximum Voluntary Contraction: maximum force, which a human participant can produce in a specific isometric exercise. In practice, the strongest contraction out of three efforts in a single test session is used.
SCM	Musculus sternocleidomastoid.
TRP-UP	Musculus trapezius pars descendens.
TTL	Taxi, Take-off and Landing position: the most upright seat position, which is the required position during Taxi, Take-off and Landing of the aircraft for safety reasons.
VAS	Visual Analogue Scale: an instrument to measure a characteristic or attitude across a continuum range of values.
VDU	Visual Display Unit: a device for displaying input signals as characters on a screen.

9.1. Introduction

This study investigates if a headrest supporting the head benefits the comfort of an aircraft passenger and lowers muscle activity in the neck when sitting in a reclined (slouched) posture while watching In-Flight Entertainment (IFE) in a Business Class seat.

As seat characteristics influence comfort experience (Bouwens, Hiemstra-van Mastrigt, & Vink, 2018b) in watching IFE, such an insight could lead to a new design requirement and/or recommendation for headrests of (premium) aircraft seats, but can also be used in car seats (e.g. in autonomous driving) and home and office furniture design. Improving the comfort experience is especially interesting for airlines to differentiate themselves (Vink & Van Mastrigt, 2011), since comfort is one of the decisive factors for passengers when booking a flight (e.g. business class), especially on long-haul flights (Alamdari, 1999; Bieger, Wittmer, & Laesser, 2007; Vink & Brauer, 2011).

There is a body of literature available, which discusses (preferable) neutral head angles (neutral in the sense of minimal muscle effort) with an upright or slightly reclined trunk (Ankrum & Nemeth, 2000; Braun & Amundson, 1989; Johnson, 1998; Mon-Williams, Burgess-Limerick, Plooy, & Wann, 1999; Raine & Twomey, 1997; Vink, 2016). For the position in the car, amongst others Park, Kim, Kim, and Lee (2000) and Kilincsoy, Wagner, Bengler, Bubb, and Vink (2014) presented comfortable angles. Van Veen et al. (2014) discuss neutral head angles in the context of tablet use in a car. Recommendations on head angles when using Visual Display Units (VDU) are described in Delleman, Haslegrave, and Chaffin (2004) and Psihogios, Sommerich, Mirka, and Moon (2001). However, in the context of watching IFE in a business class aircraft seat with a reclined trunk, literature remains limited.

9.1.1. Preference for a slouched posture when watching IFE/TV

The head inclination is influenced by the inclination of the trunk (Delleman et al., 2004) and the total body posture influences comfort (Naddeo, Cappetti, & D'Oria, 2015; Van Veen, Hiemstra-van Mastrigt, Kamp, & Vink, 2014). Additionally, facilitating a good posture may – in the long run – prevent musculoskeletal injuries (Delleman et al., 2004).

As observed in studies by Knijnenburg (2005), Van Rosmalen, Groenesteijn, Boess, and Vink (2009), Van Rosmalen, Groenestijn, and Vink (2010), Meziat Filho, Coutinho, and Azevedo e Silva (2015), Hiemstra-van Mastrigt (2015) and Smulders et al. (2016), most people prefer to sit in a reclined posture when watching television (TV) at home and when watching In- Flight Entertainment (IFE) during flight (see Table 9.1). Knijnenburg (2005) describes a preferred backrest recline of 30° for watching TV in a lorry. Van Rosmalen et al. (2009, 2010) propose a backrest angle of 40° for their prototype television seat for the home, based on an experiment with an office chair. Hiemstra-van Mastrigt (2015) found a preferred mean inclination for watching IFE in an economy class aircraft seat of 41°, where Smulders et al. (2016) found 32° for watching IFE in a business class aircraft seat. See Figure 9.1 and Table 9.2 for a comparison.

Table 9.1 | Preference for a slouched posture when watching IFE/TV.

Reference	Activity	Sample size (n)	Study setup	Conclusion
Knijnenburg (2005)	Watching TV in a passenger side lorry seat	16	Observation / Interview	A slouched posture was taken by participants as most comfortable for watching TV in a lorry.
Van Rosmalen et al. (2009, 2010)	Watching TV at home in a lounge seat	13	Observation / Questionnaire / Context mapping	Participants change posture frequently, and mostly have their feet off the ground. A slouched/reclined posture was most preferred and head support by a headrest was recommended to lower discomfort.
Meziat Filho et al. (2015)	Watching TV at home	1102	Questionnaire	51.4% prefers a slouched, reclined or lying posture, 31.9% regularly changes posture, 7.1% prefers an upright posture, 2.3% does not watch TV and 7.4% stated they preferred a different posture than shown in the survey.
Hiemstra-van Mastrigt (2015)	Watching IFE in an economy class aircraft seat	28	Observation / Questionnaire	A slouched posture with an upright head was taken by participants as most comfortable for watching IFE
Smulders et al. (2016)	Watching IFE in a business class aircraft seat	10	Observation / Questionnaire / Interview	A slouched posture was taken by participants as most comfortable for watching IFE. Half of the participants rested the head against the backrest and conducted <i>deorsumversion</i> of the eyes (looking 'downward'), where the other half flexed the head forward to watch the IFE screen.

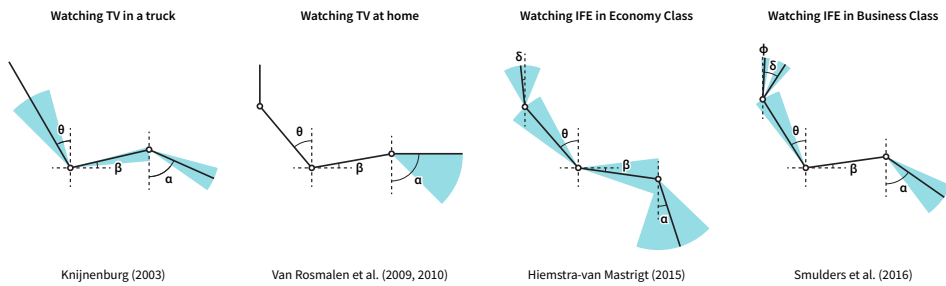


Figure 9.1 | 2D visual representation of seat angles as given in Table 9.2. Black lines represent mean values, where the blue areas represent the observed range (minimal and maximal angles, without outliers). Figure representation based on figure 5.7 from Hiemstra-van Mastrigt (2015).

Table 9.2 | Seat/body angle comparison. See Figure 9.1 for a visual representation of the given angle.

Reference	Activities	Sample size (n)	Mean legrest / lower leg angle (α)	Mean seat pan / upper leg angle (β)	Mean backrest / torso angle (θ)	Mean head angle (δ/ϕ)
Knijnenburg (2005)	Watching TV in a lorry	16	66° (SD=7.2) ¹	13° (SD=3.1) ¹	30° (SD=8.5) ¹	Set parallel to backrest ²
Van Rosmalen et al. (2009, 2010)	Watching TV in a television seat	13	90° / 45°	10°	40°	0°
Hiemstra-van Mastrigt (2015)	Watching IFE in an economy class seat	28	18° (SD=16.8°) ³	-8° (SD=6.6°) ³	41° (SD=6.1°) ³	-6° (SD=13°) ³
Smulders et al. (2016)	Watching IFE in a business class seat	10	55° (SD=11.6°)	Set at 5° ²	32° (SD=5.6°)	38° (SD=9°) / 12° (SD=7°) ⁴

¹ Data were acquired by secondary analysis of the study data of Knijnenburg (2005).

² Angle not investigated but was set.

³ Data were acquired by secondary analysis of the study data of Hiemstra-van Mastrigt (2015).

⁴ Data were acquired by secondary analysis of the study data of Smulders et al. (2016).

A possible explanation for this preference for a reclined/slouched posture may be the relative low back muscle activity in this position, as shown in the study by Goossens, Snijders, Roelofs, and van Buchem (2003). A study based on an experiment with one participant of Wilke, Neef, Caimi, Hoogland, and Claes (1999) and a study based on five participants of Rohlmann, Zander, Graichen, Dreischarf, and Bergmann (2011) may give an indication that a slouched posture also lowers pressure in the intervertebral disks. Although a multitude of in vivo spinal load studies have been conducted (Dreischarf, Shirazi-Adl, Arjmand, Rohlmann, & Schmidt, 2016), a substantial study sample is lacking to support this claim. The works of Schüldt, Ekholm, Harms-Ringdahl, Németh, and Arborelius (1986) and Schüldt, Ekholm, Harms-Ringdahl, Arborelius, and Németh (1987) show that neck muscle activity was reduced when neck flexion was increased by a backward inclination of the trunk (*thoraco-lumbar spine*).

9.1.2. Head flexion and the strain on the muscles

According to Delleman et al. (2004) the head angle is – besides the orientation of the trunk – influenced by the viewing angle on the (IFE) screen and thus its position and orientation. Kroemer and Hill (1986) show the preferred gaze angle becomes lower as the viewing distance decreases, indicating that in economy class – where space is scarcer – an IFE screen should be below eye level and oriented perpendicular to the line of sight (see Figure 9.2). Psihogjos et al. (2001) and Delleman et al. (2004) concluded in their reviews of literature on VDU viewing angles that a downward visual angle between 0° and 15° was preferred when looking at the centre of the screen, sitting in an upright position while working on input devices such as a keyboard and a mouse. The question is whether this is applicable in the context of the use of IFE in the aircraft cabin, due to the lack of intensive use of input devices (e.g. a mouse and keyboard in VDU use) and bigger variety in backrest recline (where office seats are more limited), which might result in a different preferred posture (Groenesteijn et al., 2012), head, neck and eye angle. Yoichi et al. (2012) state however that a more horizontal line of sight is preferred for further distances between the eyes and a TV screen, and thus could be more appropriate for business class with its bigger screens, generous space (bigger eye-screen distance, D) and generous backrest recline (θ) (see Figure 9.2). Also Kroemer and Hill (1986) and Mon-Williams et al. (1999) show that a more horizontal view is preferred when reclining the backrest and increasing the eye-screen distance.

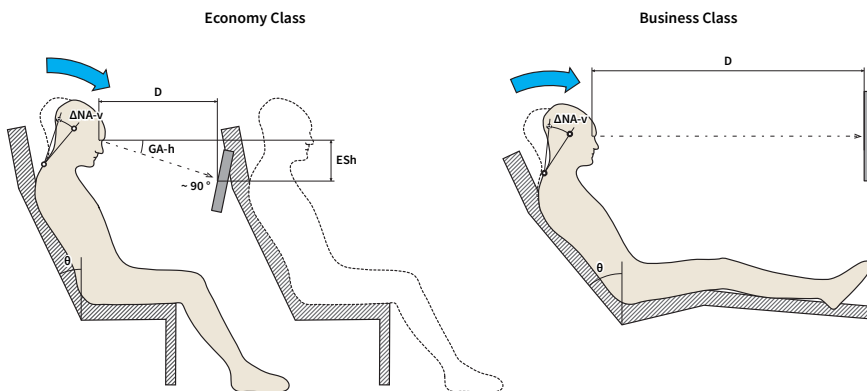


Figure 9.2 | Economy class and business class screen orientation (anatomical representation indicative only).

When reclining the backrest ($30\text{--}41^\circ$) in a business class seat while watching IFE, people tend to glare under a downward angle (*eye deorsumversion*) or flex the head forward to establish a good (horizontal) view on the IFE screen (see A and B in Figure 9.3), which was observed in the study by Smulders et al. (2016), Chapter 4 (see also Table 9.2).

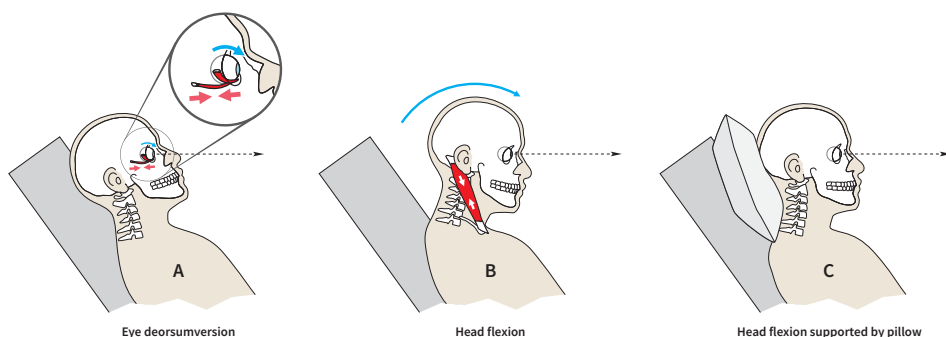


Figure 9.3 | Participant watching IFE in slouched posture while A: *deorsumversion* of the eyes by contracting e.g. the *m. inferior rectus* and *m. inferior oblique*, B: flexing the head forward with respect to the trunk by contracting e.g. the *m. sternocleidomastoid*, and C: flexing the head forward while gaining support of a pillow (anatomical representations indicative only).

However, there are indications that prolonged (e.g. when watching one or multiple movies) *eye deorsumversion* over 15° is not recommended (Delleman et al., 2004; Psihogios et al., 2001), as is prolonged (unsupported) neck flexion beyond 20° (McAtamney & Corlett, 1993) or 30° (Chaffin, 1973) which could cause muscle fatigue and the perception of discomfort by the development of a headache with pains of the head, in the area of the face, behind the eyes and in the neck (Dalassio, 1980; Travell, 1967; Travell & Simons, 1992). It can be presumed that passengers are trying to look for support when flexing the head forward (see C in Figure 9.3) by using a pillow (which is commonly supplied to passengers on long-haul business class flights).

In the studies of Van Rosmalen et al. (2009) and Smulders et al. (2016) (Chapter 4) it was observed that participants lacked neck/head support when watching TV/IFE in the slouched posture. In the study performed by Hiemstra-van Mastrigt (2015) participants reported discomfort in the neck when watching IFE in an economy aircraft seat. In a context mapping study by Van Rosmalen et al. (2010) for a TV lounge seat, participants requested a headrest for head support.

Goossens et al. (2003) show that free shoulder space and a reclined backrest lowers back muscle activity. A headrest '*pushing*' the head forward could increase the muscle activity of the neck extension muscles (e.g. *m. splenius*, *m. semispinalis* and *m. trapezius pars descendens*). But at the same time head support may lower the tension on the flexion muscles (e.g. *m. sternocleidomastoid*, *m. scalenus anterior* and *medius*). No head support could have the effect that the head is less stable and more muscle activity is required to maintain a (static) position. In a study by Lin and Huang (2007) on an economy aircraft seat, the *sternocleidomastoid* relaxed over time when using neck support in the *Taxi, Take-off and Landing position* (TTL) (i.e. the most upright position in an aircraft seat) while the *m. trapezius pars descendens* activity did not change.

In the context of watching IFE in a slouched posture, flexing the head forward with respect to the trunk without head/neck support, it could be assumed that the activity of the flexion muscles increase to maintain (static) position. The question is whether this is the case. This question could be answered by simulating using a biomechanical model and testing on participants with *electromyography* (EMG).

9.1.3. Theoretical biomechanical simulation

Neck flexion theoretically stretches the muscles posterior to the movement axis and contracts the neck muscles anterior to the movement axis. In a simulation with the musculoskeletal AnyBody™ model (see Figure 9.4), it was found that neck muscle activity decreases (see dashed lines in Figure 9.5) when the head flexes to keep a horizontal view, while the backrest was reclined at 40° and the back, buttocks, upper legs and lower arms were supported. In an AnyBody™ simulation with the model in the same context, but where a headrest supports the head/neck, the muscle activity was less for most muscles (see solid lines in Figure 9.5). The muscle tension in the *m. sternocleidomastoid* (SCM) with support of a headrest increases above -15.5°, but keeps below the muscle tension without a headrest. The muscle tension in the *m. trapezius pars descendens* (TRP-UP) with support of a headrest surpasses the simulated muscle tension without a headrest at approximately -11°, but keeps close to each other. Hypothetically a headrest should generate a force forward on the head reducing the muscle activity of muscles anterior to the flexion-extension rotation axis in the neck.

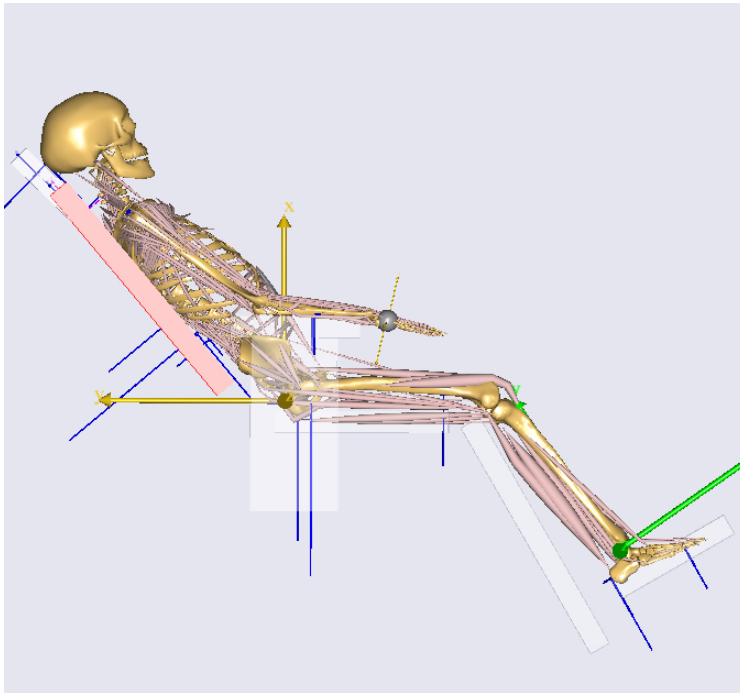


Figure 9.4 | Musculoskeletal model with supported back, buttocks, upper legs and lower arms, simulated in AnyBody™ (AnyBody Technology A/S, Aalborg, Denmark).

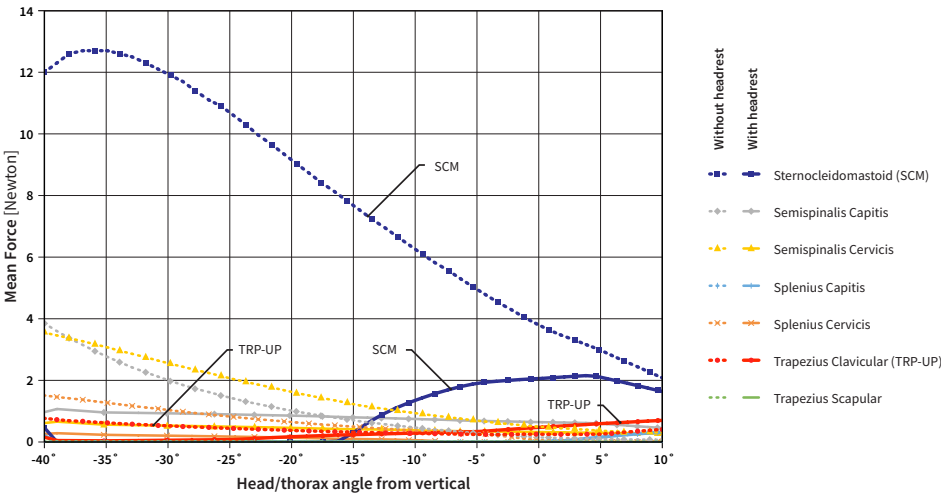


Figure 9.5 | AnyBody™ simulation of mean muscle forces [N] when head flexes from parallel to backrest (set at -40°) to upright (0°) and beyond (till 10°).

9.2. Materials and methods

To study the effect of a headrest in a slouched position, *surface electromyography* (sEMG) data, posture data and (subjective) expected long-term comfort ratings were recorded of 21 participants sitting in a lounge seat with a backrest recline of 40° , simulating an aircraft business class seat. Surface EMG was recorded of the *m. trapezius pars descendens* (TRP-UP) and *m. sternocleidomastoid* (SCM) for 5 min in each condition. Postures in the different conditions were recorded by camera. Expected long-term comfort ratings were recorded using a questionnaire.

9.2.1. Participants

11 female and 10 male American (4), Chinese (1), Dutch (15) and Iranian (1) adults with no injuries and/or physical complaints in the neck area in the past six months and who had experience as aircraft passengers in the past participated in this study (see Table 9.3). Participants were asked to wear top clothing without a collar – preferably a T-shirt – for easy sensor placement.

Table 9.3 | Characteristics of participants.

		Mean	SD
Male (n=10)	Age [years]	31.9	6.4
	Stature [cm]	1.81	0.04
	Weight [Kg]	87.2	21.6
Female (n=11)	Age [years]	24.4	1.0
	Stature [cm]	1.72	0.08
	Weight [Kg]	64.9	8.7

9.2.2. Experimental setup and stimuli

The study took place at two different locations with the exact same setup and EMG equipment. Seven participants were tested at the Human Factors and Ergonomics lab of Safran Seats US (formerly Zodiac Seats US LLC) in the USA and fourteen at the ID-user labs of the Delft University of Technology in the Netherlands.

Surface electromyography (sEMG) was used to measure muscle tension in the *m. sternocleidomastoid* (SCM) and *m. trapezius pars descendens* (TRP-UP) in three conditions for 5 min each: lying flat (condition A), sitting slouched watching IFE with a headrest (condition B) and without a headrest (condition C). Here 12 participants started in the condition with headrest (order A, B and C) and 9 without headrest (order A, C and B). To stimulate full muscle relaxation in condition A (which functions as a benchmark of full relaxation), participants were asked to lay down (on their back) on a mattress with a pillow (see Figure 9.6) in a dark room.



Figure 9.6 | Mattress with pillow for full relaxation measurement (condition A).

To simulate a TV/IFE watching posture for conditions B and C, participants sat slouched in an IKEA® POÄNG lounge seat with a $\pm 40^\circ$ reclined backrest and leg support, facing a 15" LCD monitor with a 1440 × 900 resolution (further named IFE screen) featuring a TED (a media organisation which posts talks on Technology, Entertainment and Design online for free distribution) talk on the participants' interest (via www.ted.com/topics). The IFE screen was placed at a 1.69 m distance and the screen height was set at each participant's eye height (as recommended by Yoichi et al. (2012)). In condition B the seat had a headrest (see Figure 9.7), in condition C the headrest was removed (see Figure 9.8). It is important that participants rest their arms on their lap in condition B and C, to limit

influence of carrying the load of the arms (which is 10% of the total body weight load (Roebuck, Kroemer, & Thomson, 1975; Snijders, Nordin, & Frankel, 1995) on muscle activity in the shoulder-neck region.



Figure 9.7 | Condition B: participant sitting in the seat with headrest.



Figure 9.8 | Condition C: participant sitting in the seat without headrest.

After each condition participants were asked to complete a questionnaire on their expected long-term comfort; the comfort they expect to experience after prolonged watching IFE for 3–4 h (the extended duration of one or two movies) in the

same seat position in an aircraft. A score needed to be given for the neck, head and eyes specifically and for the whole-body experience by drawing a vertical line on a horizontal visual analogue scale (VAS)-line with “*not comfortable*” and “*very comfortable*” at its ends (Bouwens, Schultheis, Hiemstra-van Mastrigt, & Vink, 2018a). For each given score, participants were asked to elaborate in writing.

To put the measured muscle tension (sEMG) into perspective, participants conducted a maximal voluntary contraction (MVC) of the neck muscles at the end of the study, by flexing the head against a load created by a TheraBand™ Red (medium strength) or Green (heavy strength, for physically stronger participants), and extending the head against the headrest (exercise inspired by Murray, Lange, Nørnberg, Sjøgaard, and Sjøgaard (2015)).

9.2.2.1. Muscle selection

For holding the head upright for watching TV/IFE in a slouched posture, the flexion and extension muscles seem most relevant to investigate.

Surface EMG (sEMG) is more suitable to record superficial muscles with their belly located directly beneath the skin surface (Stanton, Hedge, Brookhuis, Salas, & Hendrick, 2004). Therefore the *m. sternocleidomastoid* (SCM) – which is responsible for head flexion – and the *m. trapezius pars descendens* (TRP-UP) – which is responsible for extension – were selected.

Although the *m. splenius capitis* (SPL) – which performs extension (Conley, Meyer, Feedback, & Dudley, 1995) – has some tissue directly under the skin, it is mainly covered – including its muscle belly – by the *m. trapezius*. Measuring the SPL at the small lateral surfacing part at the lateral portion of the neck (approximately at C4 level, 2 cm lateral to midline (Lockhart, Hamilton, & Fyfe, 1972; Sommerich, Joines, Hermans, & Moon, 2000)) may result in measuring crosstalk of the TRP and SCM (Mayoux Benhamou, Revel, & Vallee, 1990). Although Sommerich et al. (2000) cite multiple studies that measured the splenius with sEMG, Mayoux Benhamou et al. (1990) argue it can only be measured by fine-wire or needle electrodes. It was therefore decided to exclude the SPL from this study.

9.2.2.2. EMG sensor positions

The two Trigno™ EMG sensors (electrodes) were applied parallel to the assumed muscle fibres' direction on the dominant middle portion of the muscle belly (Delsys Inc, 2012; Konrad, 2005). Muscle belly positions were palpated (by the researcher) and the sensor for the TRP-UP was placed at C5/C6 level, ±2 cm lateral to midline (positions based on Keshner, Campbell, Katz, and Peterson (1989), Konrad (2005), Queisser, Blüthner, Bräuer, and Seidel (1994), Soderberg (1992) and Zipp (1982)) and the sensor for the SCM was placed on the lower 1/3rd between the sternal notch and mastoid process (positions based on Davis (1959), Falla, Dall'Alba, Rainoldi, Merletti, and Jull (2002), Keshner et al. (1989), Soderberg (1992) and Zipp (1982)), as shown in Figure 9.9. Since the head was kept parallel to the lateral plane, only muscle activity at one side (right side) was measured.

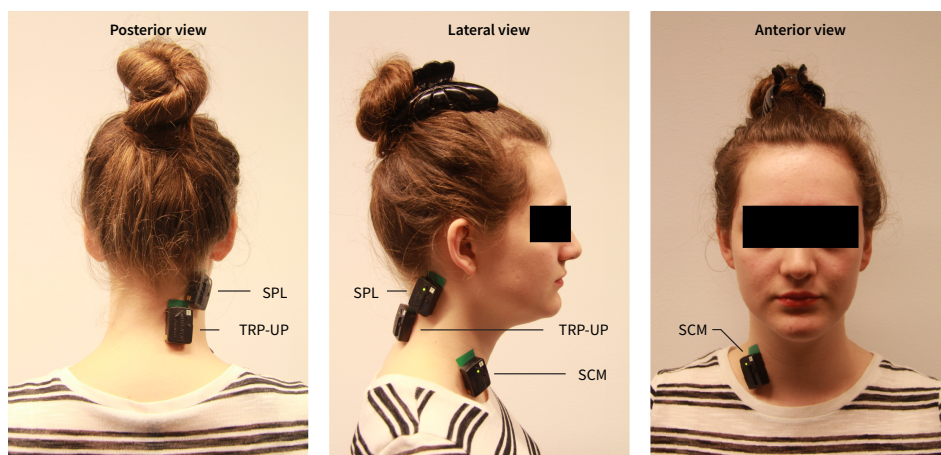


Figure 9.9 | Posterior, lateral and anterior view of sensor placement on the *splenius* and *semispinalis* area (SPL) (excluded from study, as described in §9.2.2.1), the *trapezius pars descendens* (TRP-UP) and the *sternocleidomastoid* (SCM).

9.2.3. Apparatus

A Delsys® Trigno™ Wireless EMG System (2000 Hz sampling rate) and a laptop with Delsys® EMGworks™ were used to measure and process muscle activity of the neck muscles. A Mitutoyo® digital protractor angle gauge was used to check the seat backrest to an angle of approximately 40°. In the USA a Canon® 6D DSLR camera with a Canon® EF 24–105 mm f/4.0L IS USM (set to 24 mm) at a fixed position (1.38 m lateral of the seat) was used to capture the posture at the sagittal plane. In The Netherlands, at the same distance and position a Canon® 60D DSLR camera with a Canon® EF-S 17–55 mm f/2.8 IS USM (set to 17 mm) was used. All instrumentation used was set to SI units.

9.2.4. Procedure

9.2.4.1. Participant briefing and preparation

Participants were first briefed on the procedure of the study and were then asked to sign a consent and NDA form, and state their date of birth and nationality. Participants were then requested to take off their shoes (shoes were off for the duration of the study) to measure their weight and stature. Next, participants were asked to take a seat in preparation of sensor placement.

9.2.4.2. Skin preparation and sensor placement

Areas for sensor placement on the participant's skin were cleaned by removing dead skin cells, oils and other skin surface 'pollution' by sticking and peeling 3M Transpore™ surgical tape multiple times on the skin and then softly rubbing alcohol wipes on the skin (Delsys Inc, 2012; Hermens, Freriks, Disselhorst-Klug, & Rau, 2000; Konrad, 2005). Sensors were placed on the participant's lateral right as described in §9.2.2.2.

9.2.4.3. Signal validity check

The validity of the EMG signal was checked by inspecting the baseline noise ratio, baseline offset and baseline shift (Konrad, 2005). The raw EMG signal of the SCM was inspected by letting participants flex their head forward to the opposite side (Soderberg, 1992). The same was done for the TRP-UP by having participants raise their shoulders (Soderberg, 1992).

9.2.4.4. Condition A: lying flat

Participants were asked to lie flat (on their back) on a mattress with a pillow and to fully relax for 5 minutes first (see Figure 9.6). During this period the room was darkened to help participants to fully relax. This measurement functioned as the benchmark for full muscle relaxation.

9.2.4.5. Preparing sitting position

Participants were asked to sit in the lounge seat in a slouched posture (back against reclined backrest) while resting the head against the headrest, looking forward in a preferred head angle and rest the arms in their lap. The height of the IFE screen was adjusted to meet the participant's eye height with the IFE screen's centre (Yoichi et al., 2012) and the height of the headrest was adjusted to make the headrest support the neck and head. Thereafter the participants were asked to stand up and select a TED talk movie of their interests.

9.2.4.6. Condition B: sitting slouched with headrest

Participants were asked to sit in a slouched posture (back against reclined backrest) while resting the head against the headrest, rest the arms in their lap and watch a TED-talk movie (see Figure 9.7) while EMG signals were continuously recorded for 5 min during this activity. In the last minute a lateral picture of the posture was taken and then the TED-talk movie was paused. Then the participant was asked to fill in the expected long-term comfort questionnaire. Thereafter the participants were asked to stand up and take a break for 2 minutes, to minimise fatigue (Tan, Chen, & Rauterberg, 2010).

9.2.4.7. Condition C: sitting slouched without headrest

The headrest of the seat was removed and participants were asked to watch a TED-talk movie for 5 min, but without resting the head against the seat (see Figure 9.8). The same procedure as in condition B was followed.

9.2.4.8. Maximal voluntary contraction

Lastly participants were asked to conduct a maximal voluntary contraction (MVC) of the flexion and extension neck muscles. This was executed at the end of the study, since MVC might have some discomfort effects due to extensive contractions of the muscles, which require some recovery afterwards.

Participants were asked to push their head against a TheraBand® Red (medium strength) or Green (heavy strength, for physically stronger participants) – which was

connected to the seat frame – as hard as they could for 3 seconds (flexion; see Figure 9.10). They were verbally encouraged when needed. Thereafter participants had a recovery break of 30 seconds and repeated the exercise another two times. Delsys® EMGworks™ automatically determined the highest EMG of the three MVC contractions (a manual correction was made when necessary). A similar procedure was followed to determine MVC for extension by placing the headrest back on the seat and ask participants to push their head against the headrest as hard as they could for 3 seconds (extension; see Figure 9.11). This procedure was repeated another two times and the highest MVC-EMG was determined.



Figure 9.10 | MVC flexion by pushing against an elastic TheraBand® Red (medium strength).

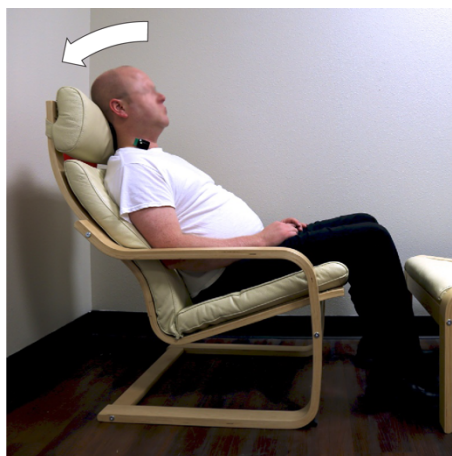


Figure 9.11 | MVC extension by pushing against the headrest.

9.2.5. Measures

9.2.5.1. Analysis of EMG

Two participants had to be excluded due to a software crash that resulted in lost or incomplete data. In analysing the EMG data first the baseline offset was removed and the root-mean-square (RMS) was calculated, creating a RA-EMG (rectified averaged EMG). Then the signal of the TRP-UP and SCM in conditions A, B and C were normalised by expressing them as a percentage of the corresponding maximum recorder MVC (%MVC). Of each data set an as large as possible sample (duration of ± 3 minutes) without noise was taken. Of these samples the mean muscle activity of the TRP-UP and SCM in each condition, expressed in %MVC, was calculated. In IBM® SPSS® Statistics a paired t-test (two tailed) was taken of the mean %MVC signals to check for significant differences ($p \leq .05$) between the conditions, as well as an independent t-test (two tailed) for influence of testing order, gender and testing location. In addition, a Pearson product-moment correlation coefficient was computed to assess influence of age, weight and stature on the muscle activity.

9.2.5.2. Analysis of expected long-term comfort rating

One participant had to be excluded due to not completing all questionnaires. All ratings were collected by measuring the given scores on the 10cm long VAS-line with a ruler and processed with IBM® SPSS® Statistics. Since comfort values cannot be assumed as being normally distributed, a more conservative Wilcoxon test was used to look for differences between conditions B and C. The significance between the scores for conditions B and C was calculated ($p \leq .05$) per rated body area (eyes, neck, head) and whole body. In addition, an independent t-test (two tailed) for influence of testing order, gender and testing location and a Pearson product-moment correlation coefficient to assess the relationship of age, weight and stature with the comfort ratings were computed.

9.2.5.3. Analysis of head-neck posture (2D)

Two participants had to be excluded from the study: one due to missing pictures of one condition, the other due to deformation of the seat by participant's weight, resulting in wrong backrest inclination. Lateral pictures taken from the fixed cameras were analysed using Adobe® Illustrator™. First, reference points were placed on the *hip joint*, *C7 (spinous process)*, *tragus*, *canthus* and visual target (the centre of the IFE screen), and then lines were drawn between those points (see Figure 9.12). The angle of each line in space was recorded (based on Psihogios et al. (2001)) and processed in IBM® SPSS® Statistics. A Wilcoxon (two tailed) test was taken of each angle to check for significant differences between the conditions ($p \leq .05$), as well as an independent t-test (two tailed) for influence of testing order, gender and testing location and a Pearson product-moment correlation coefficient was computed to assess the influence of age, weight and stature on the taken posture.

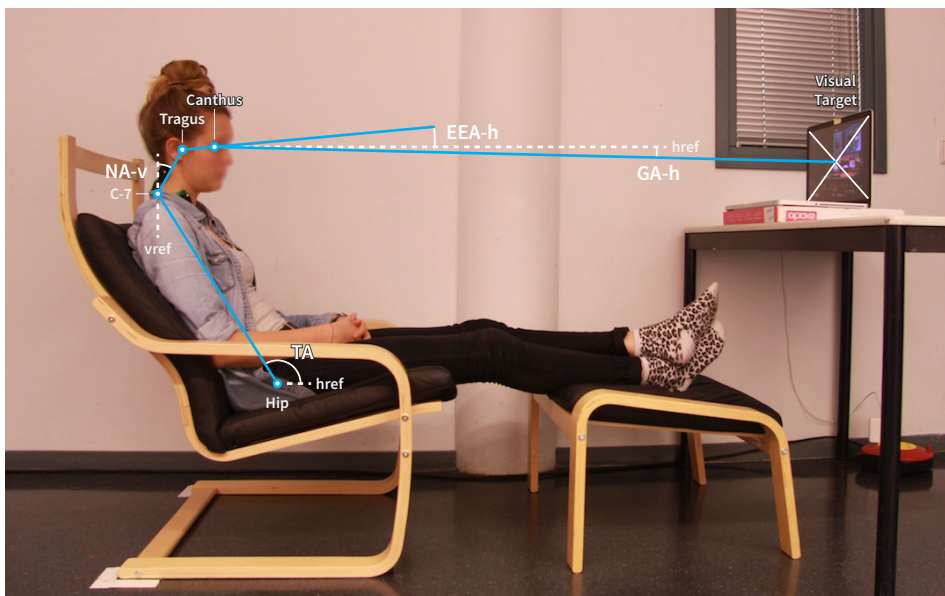


Figure 9.12 | Posture analysis, where the following angles describe the head-neck posture: TA: Trunk Angle (through hip-joint and C7) relative to horizontal, NA-v: Neck Angle (through C7 and *Tragus*) relative to vertical, EEA-h: Eye-Ear Angle (through *Tragus* and *Canthus*) relative to horizontal, GA-h: Gaze Angle (through *Canthus* and centre of the visual target) relative to horizontal. Angle representation based on Psihogios et al. (2001).

9.3. Results

The recorded mean muscle activity of the TRP-UP and SCM for conditions A, B and C, expressed as a percentage of the MVC, is shown in Figure 9.13. The EMG data show no significant difference in both the TRP-UP and the SCM between condition B and C (see Table 9.4). The SCM showed a low activity level (2%MVC on average). No significant influence of study location, gender, age, stature and testing order on the comfort scores was found, except for weight which has moderate correlations with the TRP-UP in conditions A ($r = .565, p = .01$), B ($r = .538, p = .02$) and C ($r = .574, p = .01$).

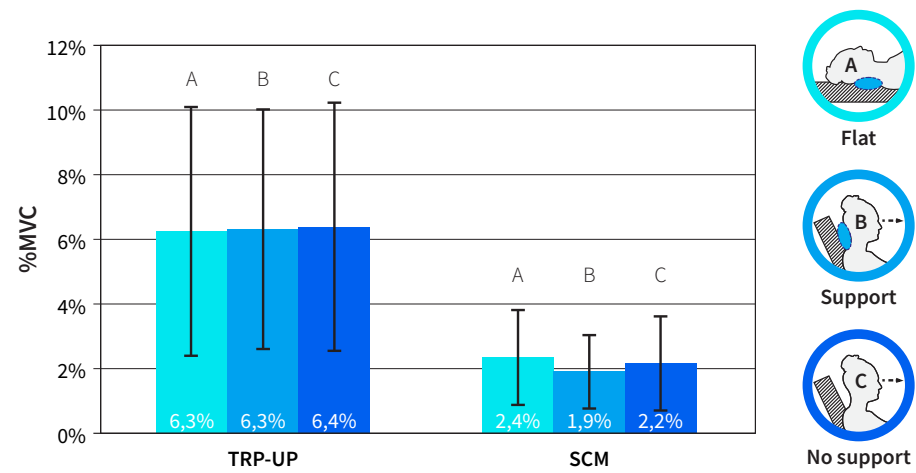


Figure 9.13 | Mean muscle activity as a percentage of MVC (n=19).

Table 9.4 | T-test (2-tailed) of muscle activity as a percentage of MVC (n=19).

Condition	SCM	TRP-UP
AB	.006 *	.7
AC	.4	.5
BC	.1	.7

Expected long-term comfort scores for whole-body comfort, neck comfort, head comfort and eye comfort are shown in Figure 9.14. Whole body ($p = .003$), head ($p < .001$) and neck comfort ($p = .001$) were significantly higher in the condition with a headrest (condition B). There was no significant difference found for the eyes ($p = .411$). No significant influence of study location, gender, age and stature on the comfort scores was found, except for a correlation between testing order and eye comfort in condition B ($r = -0.589, p = .006$).

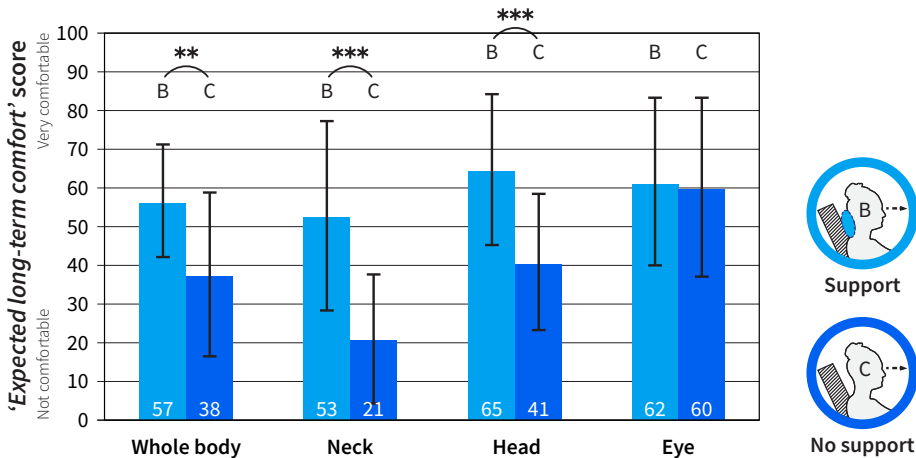


Figure 9.14 | Mean 'expected long-term comfort' scores with SD (n=20).

The inclinations describing the head-neck posture in conditions B and C can be found in Table 9.5 and are visualised in Figure 9.15. The inclination data show that the posture was significantly different between condition B and C. Without head support (C) the head was found to be more upright (vertical) in respect to with head support (B). A significant difference was found between the study locations for TA (B) ($p = .001$), TA (C) ($p = .03$) and EEL-h (B) ($p = .03$), between genders for TA (B) ($p = .007$) and between testing order for NA-v (C) ($p = .001$) and EEL-h (B) ($p = .02$). Correlations are also found between age and TA (B) ($r = .615$, $p = .005$) and TA (C) ($r = .662$, $p = .002$), weight and TA (C) ($r = .582$, $p = .009$) and stature and TA (C) ($r = .578$, $p = .01$). However, no moderate or strong correlations have been found between the amplitude of movement of TA (condition B minus C) and study location, gender, age, stature and testing order.

Table 9.5 | 2D posture inclinations (n=19).

See Figure 9.15 for a visual representation of the given angle.

Angle	TA		NA-v		EEL-h		GA-h	
Condition	B	C	B	C	B	C	B	C
Mean	126.3°	124.5°	18.0°	29.0°	23.6°	13.8°	-2.6°	-2.2°
SD	2.5°	2.7°	4.0°	3.5°	5.6°	5.3°	1.0°	1.2°
Max	132.8°	131.4°	24.7°	35.7°	36.2°	27.6°	-0.9°	0.6°
Min	123.3°	120.6°	11.5°	23.4°	14.7°	5.2°	-5.5°	-5.0°
Difference (mean)	1.9°		11.0°		9.9°		0.4°	
Wilcoxon (2-tailed)	.001 ***		.001 ***		.001 ***		.007 **	

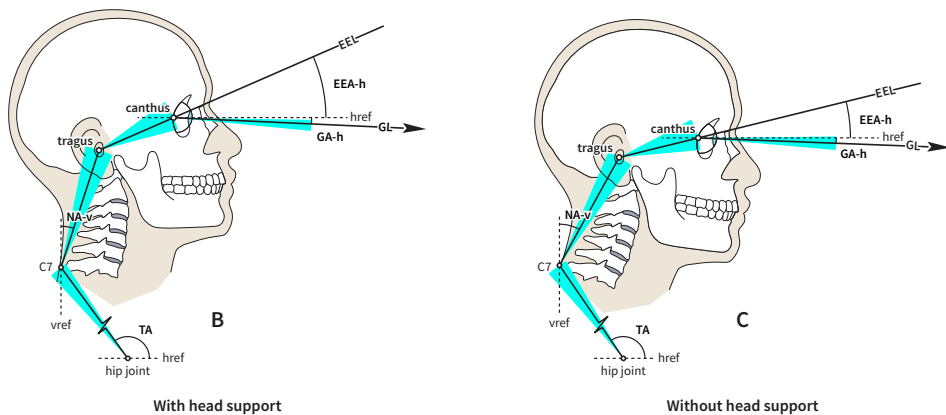


Figure 9.15 | 2D posture angles (anatomical representation indicative only) ($n=19$). Left: condition B, with head support. Right: condition C, without head support. Black lines represent mean values, where the blue areas represent the observed range (minimal and maximal angles). The given angles: TA: Trunk Angle (through *hip-joint* and C7) relative to horizontal, NA-v: Neck Angle (through C7 and *Tragus*) relative to vertical, EEA-h: Eye-Ear Angle (through *Tragus* and *Canthus*) relative to horizontal, GA-h: Gaze Angle (through *Canthus* and centre of the visual target) relative to horizontal. The given lines: EEL: Eye-Ear Line (through *Tragus* and *Canthus*), GL: Glare Line (through *Canthus* and centre of the visual target). Angle representation based on Psihogios et al. (2001).

9.4. Discussion

9.4.1. Muscle activity and fatigue

The hypothesis that the use of a headrest will reduce the neck muscle activity anterior to the movement axis of the neck could not be supported in this study. While it could be expected based on the AnyBody™ simulations (as described in §9.1.3), there was no significant difference found in muscle activity between the conditions with (B) and without head support (C). It is important to note that the EMG signals were very low (1–10%MVC), making observing differences between the conditions difficult.

According to Jørgensen, Fallentin, Krogh-Lund, and Jensen (1988), a static isometric contraction of 5–10% MVC for 1 h may result in fatigue. Jonsson (1978) suggests that a static load level ought not to exceed 5% MVC for work tasks of long duration. A study of Sjøgaard, Kiens, Jørgensen, and Saltin (1986) showed similar results, where isometric knee extension of 5% MVC sustained for 1 h caused fatigue. The muscle tension of the SCM in this study was below 5% MVC for 5 min contraction, indicating that the muscle tension may not cause fatigue. The TRP-UP however shows a MVC over 5% for 5 min contraction, indicating that fatigue may occur in the long term in the shoulder-neck region.

The positive moderate correlation between weight and muscle activity in the TRP-UP could be explained by the additional load of tissue of the head and perhaps the arms on the neck-shoulder muscles.

9.4.2. Expected long-term comfort

Expected long-term comfort was rated highest in the condition with a headrest (B), indicating there may be a positive effect on comfort through stability, support and body contact. Franz, Durt, Zenk, and Desmet (2012) describe a similar effect of body contact, where neck support benefitted the perceived comfort of most participants. Stability offered by support of a headrest may avoid corrections by the neck to maintain stability, as (among other) breathing, blood pumping and micro limb movements require corrections of the centre of gravity of the head (and body) position in respect to the neck (and ground). Making such corrections may be a tiresome activity for neck muscles and may cause discomfort in the long term.

The expectation of a passenger of having more comfort in the long term may positively influence the actual experienced comfort of the passenger during a flight, a phenomenon described by Naddeo, Cappetti, Califano, and Vallone (2015) in the context of a bed. However, it is important to note that the '*expected long-term comfort rating*' is qualitative and gives just an indication of what participants expect to experience. As shown by Bouwens, et al. (2018a), it is not always possible to predict the experienced comfort based on expected comfort. Studies that investigate long-term comfort and discomfort (around 2–3h) show the importance of long-term assessment with participants (e.g. Hiemstra-van Mastrigt, Meyenborg, and Hoogenhout (2016), Smulders et al. (2016) (see Chapter 4) and Sammonds, Fray, and Mansfield (2017); see also §2.2.6), as in time comfort usually decreases and discomfort increases (Vink, Anjani, Smulders, and Hiemstra-van Mastrigt (2017); see also Chapter 3).

9.4.3. Posture

The posture between conditions B and C was significantly different. Without head support the head was found to be more upright (vertical) and placed above the rotation axes of the neck. The reason for not finding any difference in the EMG (and the low EMG signals) could be that humans have the tendency to look for a neutral head position. This can be supported by Delleman et al. (2004), who stated that a close to neutral position is preferred, and in existing guidelines for preventing Work-Related Musculoskeletal Disorders (WMSDs) like OCRA and RULA (Stanton et al., 2004), which promote neutral neck positions. Here '*neutral*' refers to the position in which the least energy is needed to keep the head upright. Apostolico, Cappetti, D'Oria, Naddeo, and Sestri (2014) also confirmed that the most comfortable posture is within the range of the rest posture, where the neck is close to the neutral position. The posture taken in the condition with headrest (B) was dictated by the position and design of the headrest on the seat. It can be questioned if this position and the headrest design is ideal, since another position or design could create a different load on the body and thus another comfort experience. Vink (2016) suggested (based on Raine and Twomey (1997), Johnson (1998), Ankrum and Nemeth (2000) and Van Veen et al. (2014)) a neutral head position lies between 40 and 44° while sitting upright. The mean neck angle (NA-v) in this study in the condition without the headrest (C) was 29.0° while sitting slouched, and thus was different to earlier findings as cited by Vink (2016). Therefore, further research is needed on the ideal position and design of the headrest in the context of watching IFE in the aircraft.

The difference of posture between testing locations, genders and age possibly could be explained by weight and stature, as the USA testing location only had male participants who were also significantly older than the participants of the Netherlands location. Males are also generally longer and weigh more than females, this could thus explain the difference. That said, weight and stature only had a moderate correlation with TA in condition C. However, no moderate or strong correlation has been found between the amplitude of movement of TA (condition B minus C).

9.4.4. Study limitations and suggestions

Although it is not uncommon to conduct a comfort study for headrest for the limited duration of 5 min (Franz et al., 2012), due to the limited context (the limited duration of EMG measurement and comfort assessment of 5 min) of this study, only indications for long-term effects can be given. Also muscle fatigue (Sjøgaard et al., 1986) and discomfort (Sammonds, Fray, & Mansfield, 2014; Vink, 2004, 2016) were not recorded, since their impact could only be assessed properly over a longer period of time. Since passengers may watch IFE for a prolonged period of time (e.g. watching multiple movies on a long-haul flight), it is recommended to study the long-term effects of this slouched posture, with and without head support, on passenger comfort and discomfort against muscle activity and fatigue over time. It is also recommended to include a study on posture changes and (micro)movements, since they may give an indication of discomfort (Sammonds et al., 2017) and give requirements on posture allowance by the seat design. In addition, it is also recommended to study the (thoracic and lumbar) spine comfort, since these could be affected by the change in posture due to the presence of head support.

In addition, the Trigno™ EMG sensors (electrodes) used in this study were 15 mm thick and thus may be uncomfortable when in contact with the headrest, as electrodes pushed into the skin under load of the head. Participants were asked to ignore this and to exclude the sensors from their comfort assessments. However, the sensors still could have influenced the perceived comfort of the participants. Less invasive sEMG electrodes (e.g. more traditional wired pinch ECG/EEG/sEMG/EOG electrodes) are therefore advised in studying comfort in situations where the electrode may be between the human body and a contact surface, such as a seat and headrest.

9.5. Conclusion

In this study no significant differences in muscle activity (based on EMG) were found between the condition with and without head support when watching IFE in a slouched posture. A significant difference in expected long-term comfort rating was found, where it was rated highest in the condition with a headrest, indicating that a headrest may have a positive effect on the user expectations and thus (comfort) experience during flight. This study also found a significant difference in posture. Without headrest the head was found to be more upright (vertical). The lack of significant difference in EMG and the significant difference in posture between the conditions with and without headrest may indicate that humans tend to look for a head position that is neutral, in the sense of minimal (muscle) effort. Further research is advised on the design of a headrest and the long-term comfort and discomfort effects of such head support.

9.5.1. Relevance for the industry

The use of a headrest could positively influence the expected long-term comfort of the user/passenger. A headrest has an effect on the posture people take, but effects of the headrest on the neck muscle activity could not be affirmed through EMG. Implementing head support for slouched postures when watching an IFE, TV, ICE/IVI or VDU screen in premium cabin aircraft seats, (autonomous) car seats and home/office/cinema furniture may improve the user comfort. However, the long-term comfort and discomfort effects of such head support are unclear and further research is therefore needed.

9.6. Conflicts of interest

This study was financially supported by Safran Seats US (formerly Zodiac Seats US LLC). The sponsor had no influence on any decision nor execution of this study, including study design, data collection, analysis, data interpretation, writing and publication.

9.7. Acknowledgements

We want to thank dr.ir. J.M.A. Bouwens, dr.ir. S. Hiemstra-van Mastrigt, ir. S. Akkerman, ir. D.M. Lips and dr. Y. Song for their contribution, and a special thanks to mr. S. Snider and mr. B.J. Naagen for their great help and support in setting up this study. We also want to thank prof.dr.ir. R.H.M. Goossens for sharing his knowledge on biomechanics, ms. W. van der Horst for proofreading and Safran Seats US (formerly Zodiac Seats US LLC) for lending the EMG equipment and financially supporting this study. And last but not least we want to thank all the volunteers who were so kind to take part in this study.

9.8. References

- Alamdari, F. (1999). Airline in-flight entertainment: the passengers' perspective. *Journal of Air Transport Management*, 5(4), 203-209. doi:10.1016/S0969-6997(99)00014-9
- Ankrum, D.R., & Nemeth, K.J. (2000). Head and neck posture at computer workstations-what's neutral? Paper presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting. doi:10.1177/154193120004403046
- Apostolico, A., Cappetti, N., D'Oria, C., Naddeo, A., & Sestri, M. (2014). Postural comfort evaluation: experimental identification of Range of Rest Posture for human articular joints. *International Journal on Interactive Design and Manufacturing (IJDeM)*, 8(2), 109-120. doi:10.1007/s12008-013-0186-z
- Bieger, T., Wittmer, A., & Laesser, C. (2007). What is driving the continued growth in demand for air travel? Customer value of air transport. *Journal of Air Transport Management*, 13(1), 31-36. doi:10.1016/j.jairtraman.2006.11.002
- Bouwens, J.M.A., Hiemstra-van Mastrigt, S., & Vink, P. (2018b). Ranking of human senses in relation to different in-flight activities contributing to the comfort experience of airplane passengers. *International Journal of Aviation, Aeronautics, and Aerospace*, 5(2). doi:10.15394/ijaaa.2018.1228
- Bouwens, J.M.A., Schultheis, U.W., Hiemstra-van Mastrigt, S., & Vink, P. (2018a). Expected versus experienced neck comfort. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 28(1), 29-37. doi:10.1002/hfm.20721
- Braun, B.L., & Amundson, L.R. (1989). Quantitative assessment of head and shoulder posture. *Archives of physical medicine and rehabilitation*, 70(4), 322-329.
- Chaffin, D.B. (1973). Localized muscle fatigue—definition and measurement. *Journal of Occupational and Environmental Medicine*, 15(4), 346-354.
- Conley, M.S., Meyer, R.A., Feeback, D.L., & Dudley, G.A. (1995). Noninvasive analysis of human neck muscle function. *Spine*, 20(23), 2505-2512. doi:10.1097/00007632-199512000-00009
- Dalassio, D.J. (1980). *Wolff's Headache and Other Head Pain*. New York, USA: Oxford University Press.
- Davis, J.F. (1959). *Manual of surface electromyography* (Vol. 59). Wright-Patterson Air Force Base, OH, USA: Aerospace Medical Laboratory, Wright Air Development Center, Air Research and Development Command, U.S. Air Force.
- Delleman, N.J., Haslegrave, C.M., & Chaffin, D.B. (2004). *Working postures and movements: tools for evaluation and engineering*. Boca Raton, FL, USA: CRC press. doi:10.1201/9781482265095
- Delsys Inc. (2012). *Trigno Wireless System: User's Guide*. Delsys Incorporated. Boston, MA, USA. Retrieved from [Delsys.com/Attachments_pdf/Trigno%20Wireless%20System%20Users%20Guide%20\(MAN-012-2-3\).pdf](https://www.delsys.com/Attachments_pdf/Trigno%20Wireless%20System%20Users%20Guide%20(MAN-012-2-3).pdf)
- Dreischarf, M., Shirazi-Adl, A., Arjmand, N., Rohlmann, A., & Schmidt, H. (2016). Estimation of loads on human lumbar spine: a review of in vivo and computational

- model studies. *Journal of biomechanics*, 49(6), 833-845.
doi:10.1016/j.jbiomech.2015.12.038
- Falla, D., Dall'Alba, P., Rainoldi, A., Merletti, R., & Jull, G. (2002). Location of innervation zones of sternocleidomastoid and scalene muscles—a basis for clinical and research electromyography applications. *Clinical Neurophysiology*, 113(1), 57-63.
doi:10.1016/S1388-2457(01)00708-8
- Franz, M., Durt, A., Zenk, R., & Desmet, P. (2012). Comfort effects of a new car headrest with neck support. *Applied ergonomics*, 43(2), 336-343. doi: 10.1016/j.apergo.2011.06.009
- Goossens, R.H.M., Snijders, C.J., Roelofs, G.Y., & van Buchem, F. (2003). Free shoulder space requirements in the design of high backrests. *Ergonomics*, 46(5), 518-530.
doi:10.1080/0014013031000063837
- Groenesteijn, L., Ellegast, R.P., Keller, K., Krause, F., Berger, H., & de Looze, M.P. (2012). Office task effects on comfort and body dynamics in five dynamic office chairs. *Applied ergonomics*, 43(2), 320-328. doi: 10.1016/j.apergo.2011.06.007
- Hermens, H.J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of electromyography and Kinesiology*, 10(5), 361-374. doi:10.1016/S1050-6411(00)00027-4
- Hiemstra-van Mastrigt, S. (2015). *Comfortable passenger seats: Recommendations for design and research*. (Doctoral dissertation), Delft University of Technology, Delft, The Netherlands. doi:10.4233/uuid:eedd25e6-c625-45e9-9d32-f818aa89c19d
- Hiemstra-van Mastrigt, S., Meyenborg, I., & Hoogenhout, M. (2016). The influence of activities and duration on comfort and discomfort development in time of aircraft passengers. *WORK*, 54(4), 955-961.
- Johnson, G.M. (1998). The correlation between surface measurement of head and neck posture and the anatomic position of the upper cervical vertebrae. *Spine*, 23(8), 921-927. doi:10.1097/00007632-199804150-00015
- Jonsson, B. (1978). Kinesiology: with special reference to electromyographic kinesiology. *Electroencephalography and clinical neurophysiology. Supplement*(34), 417-428.
- Jørgensen, K., Fallentin, N., Krogh-Lund, C., & Jensen, B. (1988). Electromyography and fatigue during prolonged, low-level static contractions. *European journal of applied physiology and occupational physiology*, 57(3), 316-321. doi:10.1007/BF00635990
- Keshner, E.A., Campbell, D., Katz, R., & Peterson, B. (1989). Neck muscle activation patterns in humans during isometric head stabilization. *Experimental brain research*, 75(2), 335-344. doi:10.1007/BF00247939
- Kilincsoy, U., Wagner, A., Bengler, K., Bubbs, H., & Vink, P. (2014). Comfortable rear seat postures preferred by car passengers. Paper presented at the 5th International Conference on Applied Human Factors and Ergonomics AHFE 2014, Kraków, Poland.
- Knijnenburg, R. (2005). *Future passengers side truck seat for DAF*. (Master Thesis), Delft University of Technology, Delft, The Netherlands. (Confidential Graduation Report).

- Konrad, P. (2005). *The ABC of EMG: a practical introduction to kinesiological electromyography*. Scottsdale, AZ, USA: Noraxon USA.
- Kroemer, K.H.E., & Hill, S.G. (1986). Preferred line of sight angle. *Ergonomics*, 29(9), 1129-1134. doi:10.1080/00140138608967228
- Lin, Y., & Huang, W. (2007). Cervical postures and electromyographic activities of related neck muscles when using a neck support pillow. *Journal of biomechanics*(40), S414. doi:10.1016/S0021-9290(07)70409-8
- Lockhart, R.D., Hamilton, G.F., & Fyfe, F.W. (1972). *Anatomy of the human body*. Philadelphia, PA, USA: J. B. Lippincott & Co.
- Mayoux Benhamou, M.A., Revel, M., & Vallee, C. (1990). Surface electrodes are not appropriate to record selective myoelectric activity of splenius capitis muscle in humans. *Experimental brain research*, 105(3), 432-438. doi:10.1007/BF00233043
- McAtamney, L., & Corlett, E.N. (1993). RULA: a survey method for the investigation of work-related upper limb disorders. *Applied ergonomics*, 24(2), 91-99. doi:10.1016/0003-6870(93)90080-S
- Meziat Filho, N., Coutinho, E.S., & Azevedo e Silva, G. (2015). Association between home posture habits and low back pain in high school adolescents. *European Spine Journal*, 24, 425-433. doi:10.1007/s00586-014-3571-9
- Mon-Williams, M., Burgess-Limerick, R., Plooy, A., & Wann, J. (1999). Vertical gaze direction and postural adjustment: An extension of the Heuer model. *Journal of Experimental Psychology: Applied*, 5(1), 35-53. doi:10.1037/1076-898X.5.1.35
- Murray, M., Lange, B., Nørnberg, B.R., Søgaaard, K., & Sjøgaard, G. (2015). Specific exercise training for reducing neck and shoulder pain among military helicopter pilots and crew members: a randomized controlled trial protocol. *BMC musculoskeletal disorders*, 16, 1-11. doi:10.1186/s12891-015-0655-6
- Naddeo, A., Cappetti, N., Califano, R., & Vallone, M. (2015). The role of expectation in comfort perception: the mattresses' evaluation experience. *Procedia Manufacturing*, 3, 4784-4791.
- Naddeo, A., Cappetti, N., & D'Oria, C. (2015). Proposal of a new quantitative method for postural comfort evaluation. *International journal of industrial ergonomics*, 48, 25-35. doi:10.1016/j.ergon.2015.03.008
- Park, S.J., Kim, C.-B., Kim, C.J., & Lee, J.W. (2000). Comfortable driving postures for Koreans. *International journal of industrial ergonomics*, 26(4), 489-497. doi:10.1016/S0169-8141(00)00020-2
- Psihogios, J.P., Sommerich, C.M., Mirka, G.A., & Moon, S.D. (2001). A field evaluation of monitor placement effects in VDT users. *Applied ergonomics*, 32(4), 313-325. doi:10.1016/S0003-6870(01)00014-X
- Queisser, F., Blüthner, R., Bräuer, D., & Seidel, H. (1994). The relationship between the electromyogram-amplitude and isometric extension torques of neck muscles at different positions of the cervical spine. *European journal of applied physiology and occupational physiology*, 68, 92-101. doi:10.1007/BF00599248

- Raine, S., & Twomey, L.T. (1997). Head and shoulder posture variations in 160 asymptomatic women and men. *Archives of physical medicine and rehabilitation*, 78(11), 1215-1223. doi:10.1016/S0003-9993(97)90335-X
- Roebuck, J.A., Kroemer, K.H.E., & Thomson, W.G. (1975). *Engineering Anthropometry Methods* (Vol. 3). NY, USA: Wiley-Interscience.
- Rohlmann, A., Zander, T., Graichen, F., Dreischarf, M., & Bergmann, G. (2011). Measured loads on a vertebral body replacement during sitting. *The Spine Journal*, 11(9), 870-875. doi:10.1016/j.spinee.2011.06.017
- Sammonds, G.M., Fray, M., & Mansfield, N.J. (2014). Overall car seat discomfort onset during long duration driving trials. Paper presented at the 5th International Conference on Applied Human Factors and Ergonomics, Krakow, Poland.
- Sammonds, G.M., Fray, M., & Mansfield, N.J. (2017). Effect of long term driving on driver discomfort and its relationship with seat fidgets and movements (SFMs). *Applied ergonomics*, 58, 119-127.
- Schüldt, K., Ekholm, J., Harms-Ringdahl, K., Arborelius, U.P., & Németh, G. (1987). Influence of sitting postures on neck and shoulder emg during arm-hand work movements. *Clinical Biomechanics*, 2(3), 126-139. doi:10.1016/0268-0033(87)90003-9
- Schüldt, K., Ekholm, J., Harms-Ringdahl, K., Németh, G., & Arborelius, U.P. (1986). Effects of changes in sitting work posture on static neck and shoulder muscle activity. *Ergonomics*, 29(12), 1525-1537. doi:10.1080/00140138608967266
- Sjøgaard, G., Kiens, B., Jørgensen, K., & Saltin, B. (1986). Intramuscular pressure, EMG and blood flow during low-level prolonged static contraction in man. *Acta Physiologica Scandinavica*, 128(3), 475-484.
- Smulders, M., Berghman, K., Koenraads, M., Kane, J., Krishna, K., Carter, T., & Schultheis, U. (2016). Comfort and pressure distribution in a human contour shaped aircraft seat (developed with 3D scans of the human body). *WORK*, 54(4), 925-940.
- Snijders, C.J., Nordin, M., & Frankel, V.H. (1995). *Biomechanica van het spier-skeletstelsel: grondbeginselen en toepassingen*. Utrecht, The Netherlands: Lemma.
- Soderberg, G.L. (1992). Recording techniques. In *Selected Topics in Surface Electromyography for Use in the Occupational Setting: Expert perspectives* (pp. 31-35). IA, USA: National Institute for Occupational Safety and Health, U.S. Department of Health and Human Services.
- Sommerich, C.M., Joines, S.M., Hermans, V., & Moon, S.D. (2000). Use of surface electromyography to estimate neck muscle activity. *Journal of electromyography and Kinesiology*, 10(6), 377-398. doi:10.1016/S1050-6411(00)00033-X
- Stanton, N.A., Hedge, A., Brookhuis, K., Salas, E., & Hendrick, H.W. (2004). *Handbook of human factors and ergonomics methods*. Boca Raton, FL, USA: CRC press. doi:10.1201/9780203489925
- Tan, C.F., Chen, W., & Rauterberg, M. (2010). Experimental design for sternocleidomastoid muscle stress measurement. Paper presented at the Proceedings

- of the 7th International Conference on Methods and Techniques in Behavioral Research, Eindhoven, The Netherlands. doi:10.1145/1931344.1931372
- Travell, J.G. (1967). Mechanical headache. *Headache: The Journal of Head and Face Pain*, 7(1), 23-29. doi:10.1111/j.1526-4610.1967.hed0701023.x
- Travell, J.G., & Simons, D.G. (1992). *Myofascial Pain and Dysfunction: the Trigger Point Manual*, vol. 2. Philadelphia, PA, USA: Lippincott Williams & Wilkins.
- Van Rosmalen, D.M., Groenesteijn, L., Boess, S., & Vink, P. (2009). Using both qualitative and quantitative types of research to design a comfortable television chair. *Journal of Design Research*, 8(1), 87-100. doi:10.1504/JDR.2009.031001
- Van Rosmalen, D.M., Groenesteijn, L., & Vink, P. (2010). Eisen aan een loungestoel om naar een scherm te kijken. *Tijdschrift voor Ergonomie*, 35(2), 4-10.
- Van Veen, S.A.T., Hiemstra-van Mastrigt, S., Kamp, I., & Vink, P. (2014). Improving car passengers' comfort and experience by supporting the use of handheld devices. *Work*, 49(2), 215-223. doi:10.3233/WOR-131716
- Vink, P. (2004). *Comfort and design: principles and good practice*. Boca Raton, Florida, USA: CRC Press. doi:doi.org/10.1201/9781420038132
- Vink, P. (2016). *Vehicle seat comfort and design: With special attention for aircraft seats*. Zwaag, The Netherlands: Pumbo.
- Vink, P., Anjani, S., Smulders, M., & Hiemstra-van Mastrigt, S. (2017). Comfort and discomfort effects over time: the sweetness of discomfort and the pleasure towards of the end. Paper presented at the 1st International Comfort Congress.
- Vink, P., & Brauer, K. (2011). *Aircraft Interior Comfort and Design*. Boca Raton, FL, USA: CRC Press. doi:10.1201/b10815
- Vink, P., & Van Mastrigt, S. (2011). The aircraft interior comfort experience of 10,032 passengers. Paper presented at the Proceedings of the Human Factors and Ergonomics Society 55th Annual Meeting, Las Vegas, NV, USA. doi:10.1177/1071181311551118
- Wilke, H.J., Neef, P., Caimi, M., Hoogland, T., & Claes, L.E. (1999). New in vivo measurements of pressures in the intervertebral disc in daily life. *Spine*, 24(8), 755-762. doi:10.1097/00007632-199904150-00005
- Yoichi, I., Kazuhiko, I., Naoaki, U., Kazuyuki, K., Hiroki, K., Satoru, K., . . . Ryoji, Y. (2012). *Ergonomic Design Guidelines for Flat Panel Display Televisions*. Retrieved from www.ergonomics.jp/official/page-docs/product/guideline/TV_guide_2012_Eng.pdf
- Zipp, P. (1982). Recommendations for the standardization of lead positions in surface electromyography. *European journal of applied physiology and occupational physiology*, 50(1), 41-54. doi:10.1007/BF00952243

DENSE 3D PRESSURE DISCOMFORT THRESHOLD (PDT) MAP OF THE HUMAN HEAD, FACE AND NECK

A NEW METHOD FOR MAPPING HUMAN SENSITIVITY

This chapter has been published as:

Smulders, M., van Dijk, L. N. M., Song, Y., Vink, P., & Huysmans, T. (2023). Dense 3D pressure discomfort threshold (PDT) map of the human head, face and neck: A new method for mapping human sensitivity. *Applied ergonomics*, 107, 103919.

ABSTRACT

When designing products/wearables that interface with the human head, face and neck, designers and engineers consider human senses, ergonomics and comfort. A dense 3D pressure discomfort threshold map could be helpful, but does not exist yet. Differences in pressure discomfort threshold for areas of the head, neck and face were recorded, to create a 3D pressure discomfort threshold map.

Between 126 and 146 landmarks were placed on the left side of the head, face and neck of twenty-eight healthy participants (gender balanced). The positions of the landmarks were specified using an EEG 10–20 system-based landmark-grid on the head and a self-developed grid on the face and neck. A 3D scan was made to capture the head geometry and landmark coordinates. In a randomised order, pressure was applied on each landmark with a force gauge until the participant indicated experiencing discomfort. By interpolating all collected pressure discomfort thresholds based on their corresponding 3D coordinates, a dense 3D pressure discomfort threshold map was made.

A relatively low-pressure discomfort threshold was found in areas around the nose, neck front, mouth, chin-jaw, cheek and cheekbone, possibly due to the proximity or direct location of nerves, blood veins and soft (muscular) tissue. A medium-pressure discomfort was found in the neck back, forehead and temple regions. A high-pressure discomfort threshold was found in the back of the head and scalp, where skin is relatively thin and closely supported by bone, making these regions interesting for mounting or resting head, face and neck related equipment upon.

Abbreviations

CAD	Computer-aided design: the use of computers to aid in the creation, modification, analysis, or optimisation of a design.
EEG	Electroencephalography: an electrodiagnostic technique for evaluating and recording the electrical activity produced by the brain.
PDT	Pressure Discomfort Threshold: tissue sensitivity for pressure, determined by the amount of pressure over a given area in which a steadily increasing nonpainful pressure stimulus turns into a discomfortable pressure sensation.
PPT	Pressure Pain Threshold: deep muscular tissue sensitivity for pressure, determined by the amount of pressure over a given area in which a steadily increasing nonpainful pressure stimulus turns into a painful pressure sensation (O'Hara et al., n.d.).

10.1. Introduction

When designing products that humans touch, wear and interact with, designers and engineers always consider the human senses and ergonomics, as contact pressure of a product to the human skin has an influence on the comfort experience of use (Fenko, Schifferstein, & Hekkert, 2010; Goossens, 2009; Mergl, 2006; Vink & Hallbeck, 2012; Zenk, Mergl, Hartung, Sabbah, & Bubb, 2006). Too high contact pressure can lead to discomfort or even pain (Shah, Luximon, & Luximon, 2017). Insight on pressure sensitivity, expressed as pressure discomfort threshold (PDT) (Buso & Shitoot, 2019; Fischer, 1986; Shah & Luximon, 2021; Vink & Lips, 2017; Xiong, Goonetilleke, & Jiang, 2011) of different areas could lead to new design requirements and/or recommendations. A 3D PDT map could provide a theoretical base for adapting the interface softness, location and surface area between user and head-, eye-, ear- and face-wearables and equipment for medical, aeronautical, maritime, consumer and defence applications. Such applications could be: helmets, (medical) head mounted cameras and magnification, glasses, marine-, Augmented Reality- (AR), and Virtual Reality- (VR) goggles (W. Lee, Kim, Molenbroek, Goossens, & You, 2019) headphones, headsets, hearing aids, medical-, aeronautic-, and industrial masks and respirators (W. Lee et al., 2019; Zhuang & Bradtmiller, 2005), sleeping pillows and headrests (Franz, Durt, Zenk, & Desmet, 2012). To design more comfortable products, designers and engineers might need more detailed information on head, face, and neck sensitivity.

Many studies have been conducted on finding PDT, and/or pressure pain threshold (PPT) of the head. Antonaci, Bovim, Fasano, Bonamico, and Shen (1992) investigated pain of pressure on the *frontal*, *parietal*, *occipital*, *temporal*, *zygomatic* and *posterior-parotid* regions of the head (n=40) based on 11 symmetrical landmarks on each side of the head, where Brough and Konz (1992) investigated discomfort of pressure on the *frontal*, *parietal* and *temporal* regions of the head (n=30) based on 48 landmarks (24 left, 24 right). Hung and Samman (2009) investigated static light touch, 2-point static, and pain detection thresholds in “*normal young Chinese individuals*” (n=100) on the *infraorbital*, *upper- and lower-labial*, and *chin*, on both the left and right sides of the head, based on 8 landmarks. Shah and Luximon (2021) investigated pressure sensitivity of the human head, face and partly the neck in Chinese adults (n=218) based on 76 landmarks (38 left, 38 right).

Although researchers paid considerable efforts on head sensitivity, most of these studies were limited in sample size, gender balance, landmark density, testing region and/or availability of data. A higher landmark density could provide designers and engineers with a more precise PDT map that could enable them to design more comfortable product-user interfaces. Also, most of these studies did not cover, or only covered a limited section of the neck, where this could be crucial in designing the interfaces between human and products like neck braces, headrests and helmets.

The aim of this study is to create a high-density 3D PDT map of the head, face and neck for a better understanding of the pressure sensitivity of humans, as well as facilitating designers and engineers in designing products that interface with these regions.

10.2. Participants, materials and method

PDT was measured in 28 healthy participants on 126 to 146 landmarks (135 on average) on the left side of the head, face and neck, as previous studies found no significant differences between the left and right side of the head (Antonaci et al., 1992; Brough & Konz, 1992; Posnick, Zimbler, & Grossman, 1990; Shah & Luximon, 2021). Since previous studies indicate repeated trials give similar results (Antonaci et al., 1992; Posnick et al., 1990; Shah & Luximon, 2021), and in order to maintain the feasibility of the study with the available resources, no repeated trials were conducted. The landmarks’ 3D coordinates for each participant were captured by means of 3D scanning and mapped to a reference head. The PDT values of all participants were bilaterally mirrored and interpolated to create a complete 3D PDT map of the human head, face and neck.

10.2.1. Participants

14 female and 14 male (14 Dutch, 6 Chinese, 3 Italian, 1 Costa Rican, 1 Thai, 1 American, 1 Belgian and 1 Danish-German) adults with no history of a stroke, epilepsy, seizure, stenosis, and/or injuries or physical complaints at the face, neck and/or head in the past six months participated in this study (see Table 10.1). Participants with tape and/or glue allergies were excluded from the experiment, as sticker landmarks were used on the skin.

Table 10.1 | Characteristics of participants

		Mean	SD
Female (n=14)	Age [years]	35.4	14.4
	Stature [cm]	168.5	5.0
	Weight [Kg]	59.2	7.8
Male (n=14)	Age [years]	31.5	11.9
	Stature [cm]	179.1	9.5
	Weight [Kg]	73.6	7.9

10.2.2. Apparatus

Pressure gauges have been used in the past to measure PPT (e.g.Antonaci et al. (1992), Fischer (1986) and Shah and Luximon (2021)) and PDT (e.g. Broekhuizen, De Rydt, Lutters, Ten Klooster, and De Bruyne (2019), Buso and Shitoot (2019), Shah and Luximon (2021) and Vink and Lips (2017)). In this study, a Mecmesin AFG 500N pressure gauge was used to apply pressure stimuli perpendicular to the skin on landmarked locations (see Figure 10.1), capturing the PDT in Newtons.



Figure 10.1 | Mecmesin AFG 500N pressure gauge with 3D printed PLA Ø10 mm tip, and participant with EEG 10–20 landmark grid headcap and landmark stickers on the face, head and neck. Researcher gradually increasing pressure on a landmark with pressure gauge until the participant indicates the PDT has been reached.

Where Vink and Lips (2017) used a $\varnothing 20$ mm probe tip for probing the buttocks and back, Fischer (1987) and Broekhuizen et al. (2019) used a 1 cm^2 probe, and Antonaci et al. (1992), Brough and Konz (1992) and Buso and Shitoot (2019) used a $\varnothing 10$ mm probe tip for probing the head, feet and other body parts. As a $\varnothing 10$ mm probe is small enough to capture small facial features (e.g. nose tip) for a high-density measurement, a 3D printed $\varnothing 10$ mm PLA pressure gauge probe with rounded edges (3 mm fillet) was made for this study (see Figure 10.1). Rounded edges were used to prevent high pressure at the surface edge (Buso & Shitoot, 2019; Fransson-Hall & Kilbom, 1993). PLA (Polylactic acid) was chosen for its biocompatibility (Ramot, Haim-Zada, Domb, & Nyska, 2016) and low thermal conductivity regarding metal probes, as a cold sensation might influence thermal comfort of the user (Parsons, 2003).

$\varnothing 12$ mm stickers were used as landmarks. A hair cap was used to hygienically cover the hair, in order to place a head-cap with an EEG 10–20 landmarks grid (Jasper, 1958) (see Figure 10.1) to landmark the positions on the head. An Artec Eva 3D scanner was used to capture the 3D geometry of the head and landmark coordinates. A Canon EOS 60D camera was used to capture reference photos of the landmarks.

A massage seat was used to support the head (preventing movement and muscle activation caused by giving counter-pressure) while probing PDT.

10.2.3. Procedure

Written consent was obtained prior to the experiment. Stature and weight were measured, and age, gender and ethnicity/nationality were noted.

10.2.3.1. Landmark placement and capture

Participants were asked to clean their face and neck with hypoallergenic cleaning wipes for better landmark sticker adhesion. Researchers cleaned their hands with disinfectant alcohol gel.

Participants with long hair were asked to make a bun to the right side of the head, next to the ear, to minimise influence of the hair on the 3D scan (in order to scan close to the actual scalp) and PDT measurements.

Participants then sat down, where two researchers placed a clean hair cap over the hair and pushed hair underneath as much as possible. Next, the head-cap with the EEG 10–20 landmark grid was placed on top. 126 to 146 landmarks (135 on average) were placed by two researchers on the face and neck (see Figure 10.2). Some of these landmarks were placed based on clearly identifiable anatomical landmarks (e.g. *tragus*, *lateralis ad alare*, *philtrum*, *protuberantia mentalis*, and *commissura labiorum*, as indicated on a reference model), where others were at intermediate locations (see Figure 10.2). The goal was to gain a compact spread over the entire head, face and neck, with a distance of 2–3 cm between landmarks. Some participants with broad necks got an extra row of landmark-stickers in the back of the neck and some got extra landmarks around the ear to cover some ‘*blind spots*’.

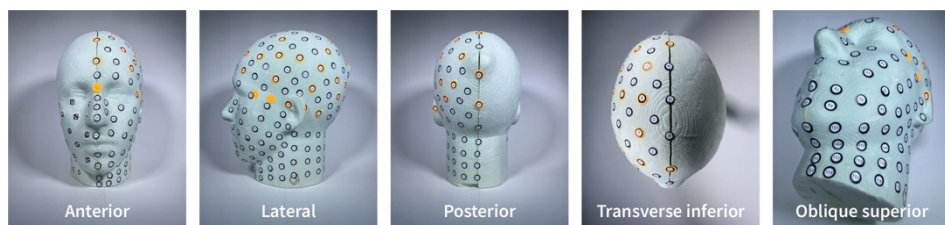


Figure 10.2 | Landmark location reference model (black landmarks only).

With an Artec Eva 3D scanner, the geometry of the head, face and neck, and the landmark coordinates were captured. Thereafter reference photos of the landmarks were made.

10.2.3.2. Sensitivity experiment procedure

All landmark-points were divided over four zones, to limit the number of postural changes, which were passed in order of A, B and C. For pressure on the head (zone 1) and the back of the neck (zone 4), participants were asked to take position A (see Figure 10.3): with the face down on the head support. For pressure on the face (zone 2), participants were asked to take position B (see Figure 10.3): with the face sideways on the headrest, respectively. For pressure on the lower chin and neck front (zone 3), participants were asked to take position C (see Figure 10.3): sitting upright, respectively.

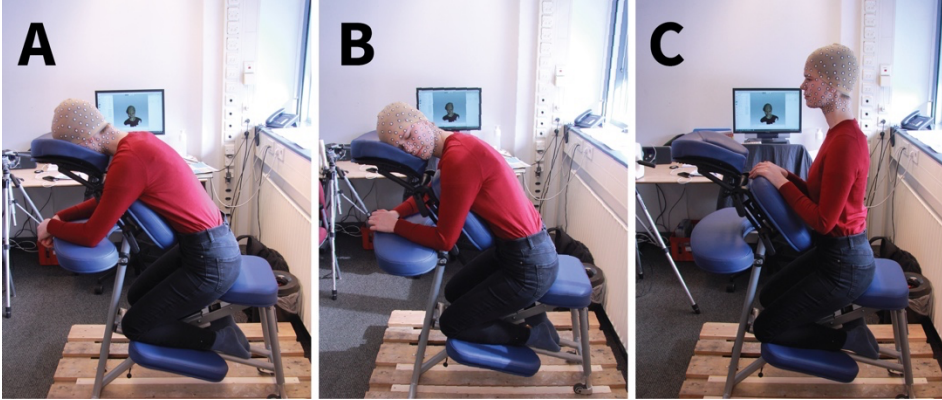


Figure 10.3 | Position A: participant in massage seat, face down. Position B: participant in massage seat, face sideways. Position C: participant in massage seat, head up.

The experiment was conducted in two sessions: the first was for priming, where participants got acquainted with the procedure with a limited number of landmarks being pressed. Thereafter participants were asked to stand up and have a 5-min break, to limit the impact of the priming on the second session. In the second session, all landmarks in each zone were probed in a randomised order and data was collected. For each landmark, a researcher gradually applied pressure on the centre of the landmark with the probe of the pressure gauge along the normal direction of the face/head/neck in this region (see Figure 10.1). Participants were instructed to slap with their hand on the arm rest when applied pressure was considered uncomfortable. Pressure was then released by the researcher and the recorded maximum force was documented.

10.2.4. Measures

10.2.4.1. 3D scan processing

In Artec Studio 14, 3D scans of each participant were pre-processed (e.g. fill holes), aligned and merged as a 3D textured mesh, which was exported in OBJ format.

10.2.4.2. 3D landmark allocation and numbering

A Python program was developed to allocate the correct landmark ID number to each landmark. Landmark IDs were visually identified based on the allocated number in the scan, or when illegible, the reference photos were used.

10.2.4.3. Intra-individual pressure distribution processing

To compare relative PDT differences between participants, the PDTs were normalised per participant by expressing the PDT as a percentage of the mean of the top 5% PDT of the individual participant. Mean5%MaxPDT was chosen to limit the effect of outliers on the normalisation.

10.2.4.4. Mean 3D head model

To create the PDT map, a mean head model was made from the 3D scans of all participants. The 3D scan of each participant was rigidly aligned with a standard head mesh template in R3DS Wrap 3.4, based on predefined landmarks on the *glabella*, *nose apex*, between the *alar nasal sulcus-nasolabial sulcus*, *philtrum*, *ear lobule* and *protuberantia occipitalis externa*. Next, the mesh template was wrapped on the 3D scan while matching the predefined landmarks (i.e. elastically deform the mesh template to match the shape of the 3D scan), which utilises a variant of the non-rigid iterative closest points algorithm (Dyke et al., 2020). The results were visually checked and interactively adjusted where needed. This process was iterated over all 28 3D scans.

Based on these 28 3D scans, a mean head model was made using a Python script (Huysmans, Goto, Molenbroek, & Goossens, 2020), where all meshes were aligned (Gower, 1975). The mean coordinates were calculated for each vertex (point), from which the mean head mesh was created. The complete process ensures a point-to-point correspondence between the mean model and each 3D scan.

10.2.4.5. Bilaterally symmetric modelling

Using the one-to-one correspondence between the mean model and each participant's 3D scan, landmark locations of each 3D scan were mapped onto the average head model. Note that, due to the manual landmark placement, the landmark locations can slightly differ between participants, and thus also end up at slightly different locations on the average head, as shown in Figure 10.4.

Bilateral symmetry was accomplished by utilizing a left-right correspondence on the average head, which was obtained by wrapping a left-right mirrored version of the average head to the original average head. By averaging the vertex coordinates of two head models, an average and symmetric head model was obtained.

In creating the symmetric average model, clipping of the surface to a region of interest (ROI) was needed. To this end the ROI was limited to those parts of the model where for 90% of the participants there was at least 1 landmark within a 30 mm range.

10.2.4.6. 3D pressure discomfort threshold map

PDT values between landmarks were obtained from a smooth interpolation of the values at landmark locations to the rest of the average head model, by solving for a solution with a vanishing Laplacian at all vertices (*method B* from Oostendorp, van Oosterom, and Huiskamp (1989)). The resulting symmetric PDT maps, defined on the symmetric average head model, allowed to calculate summary statistics of PDT over the full set of participants or for gender-specific sub-groups (e.g. see Figure 10.5-6). The same approach was used to create maps of normalised PDT values (Mean5%MaxPDT).

10.2.4.7. Statistical analysis

Where previous studies like Shah and Luximon (2021) statistically analyse individual landmarks, this study uses a method with anatomical independent landmarking in order to achieve greater landmark density. This method however does not allow for landmark based analysis, as placed landmarks do not always correspond between participants within this study and previous studies. Therefore, zones are drawn to conduct statistical analysis and compare results with previous studies. Zones *scalp*, *forehead*, *temple*, *back head*, *nose*, *cheekbone*, *cheek*, *mouth*, *jaw-chin*, *neck front*, and *neck back* are based on zones of potential interest for different wearables, anatomical features, underlying tissue, landmark locations and observed PDT transitions (see Figure 10.4).

A Mann-Whitney-Wilcoxon test (two-tailed) was used for comparing gender differences and a Kruskal-Wallis test for identifying difference in median PDT across zones ($p < .05$). A Dunn's Post-hoc (pairwise) tests was used to identify differences per combination of zones, which was compensated for multiple comparisons by controlling False Discovery Rate through the Benjamini-Hochberg procedure.

Analysis of gender difference was conducted based on both absolute- and normalised PDT data (Mean5%MaxPDT). All other statistical analyses were conducted based on absolute PDT values only (thus no interpolated nor mirrored data were used).

10.3. Results

10.3.1. Average PDT map

In Figure 10.4 the landmark dense 3D PDT map is shown. The mean and standard deviation (SD) 3D PDT maps of all participants, males and females are shown in Figure 10.5 and Figure 10.6. The standard deviation is more prevalent at the *forehead*, *scalp*, *back head* and *back neck*.

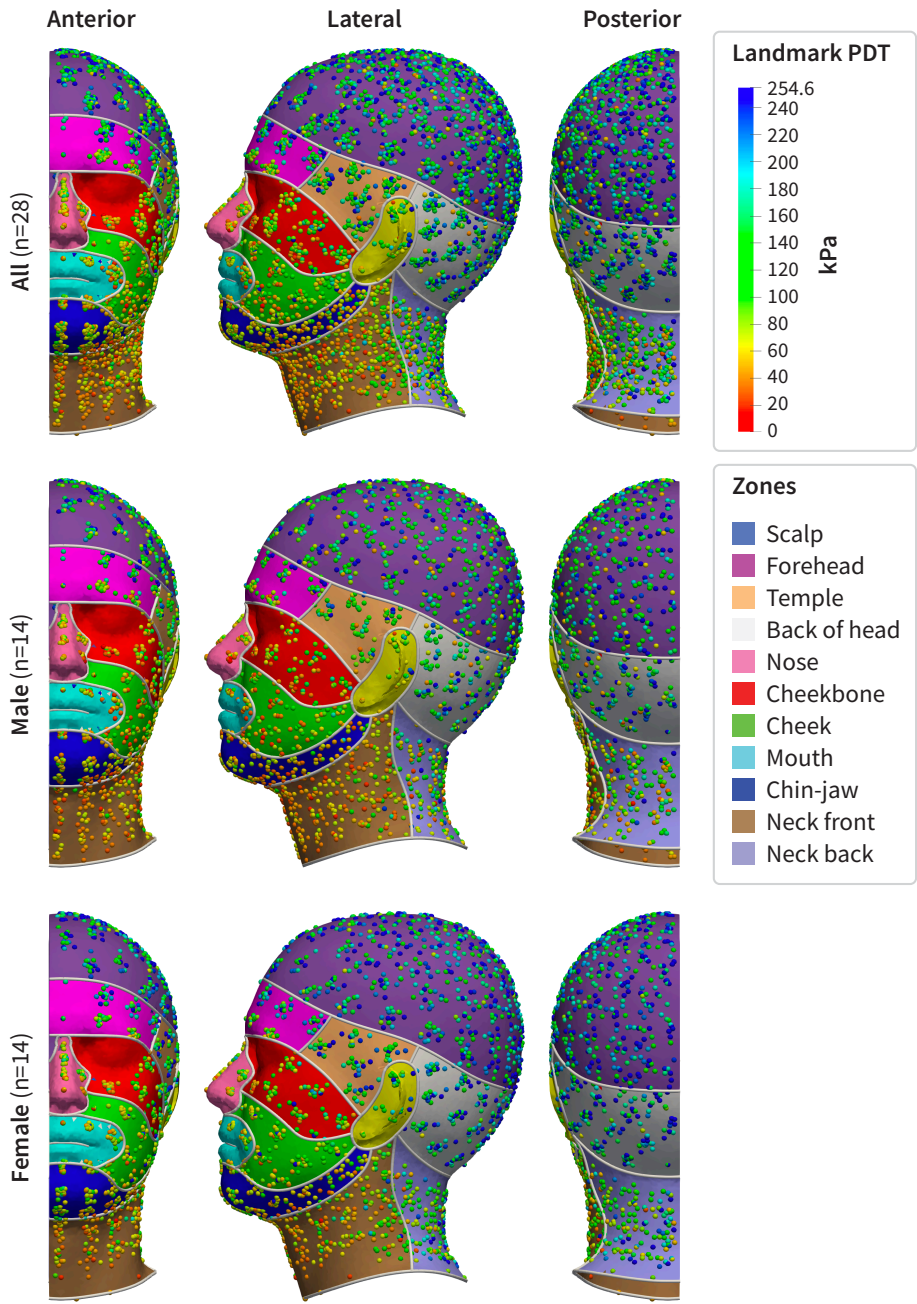


Figure 10.4 | PDT values in kPa per landmark within zones of all participants (n=28), males (n=14) and females (n=14), anterior, lateral and posterior view. Please note that shading is on to improve depth perception, which may affect colour (and thus PDT value) interpretation. The use of the digital model is advised (please see the *open data access* section at §10.6). Please note that long hair of female participants and the pressure by the headcap may influence gender and zone differences (see also §10.4.2).

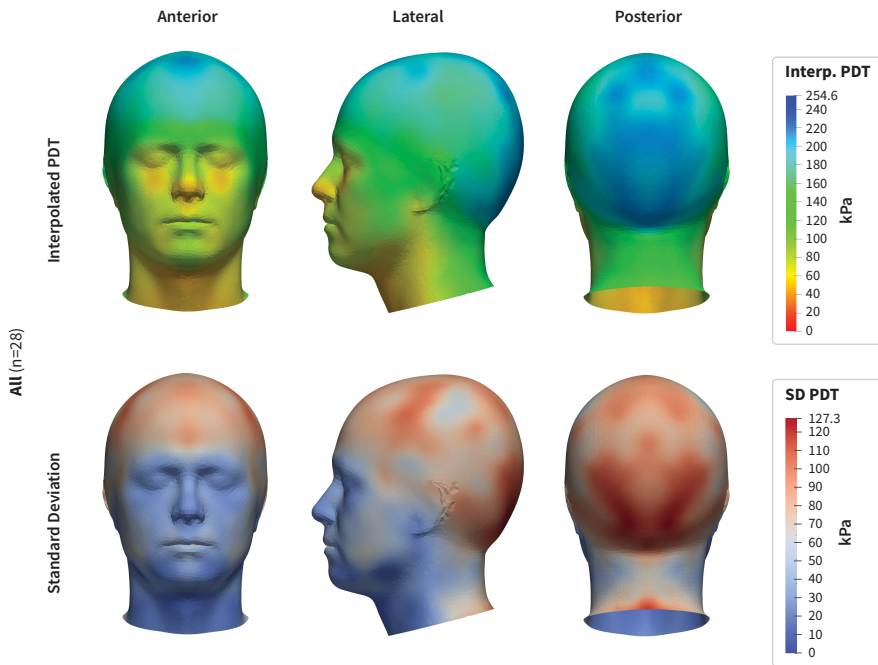


Figure 10.5 | Mean and SD interpolated PDT map in kPa of all participants (n=28), anterior, lateral and posterior view. Please note that shading is on to improve depth perception, which may affect colour (and thus PDT value) interpretation. The use of the digital model is advised (please see the *open data access* section at §10.6).

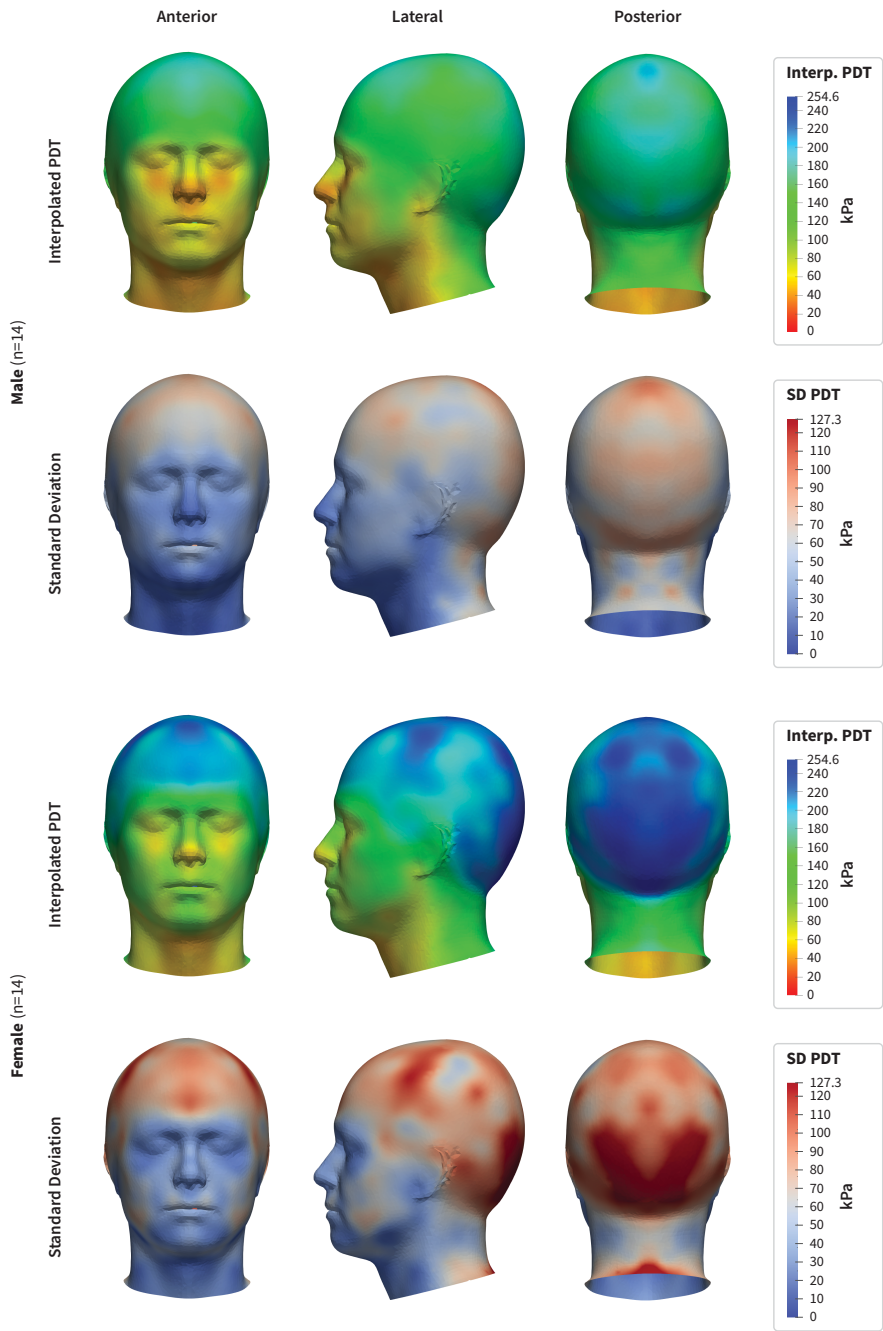


Figure 10.6 | Male and female mean and SD interpolated PDT map in kPa (n=14), anterior, lateral and posterior view. Please note that shading is on to improve depth perception, which may affect colour (and thus PDT value) interpretation. The use of the digital model is advised (please see the *open data access* section at §10.6). Please note that long hair of female participants and the pressure by the headcap may influence gender and zone differences (see also §10.4.2).

10.3.2. PDT gender difference

Figure 10.6 shows that females have a higher PDT than males. This is also true when looking at differences per zone (see Figure 10.7 and Table 10.2). However, normalised PDT values (based on the Mean5%MaxPDT) of each landmark within each zone for males and females only significantly differ on the *scalp*, *back of the head* and *mouth* (see Figure 10.8 and Table 10.2). This indicates that PDT is similarly distributed in males and females for the other zones.

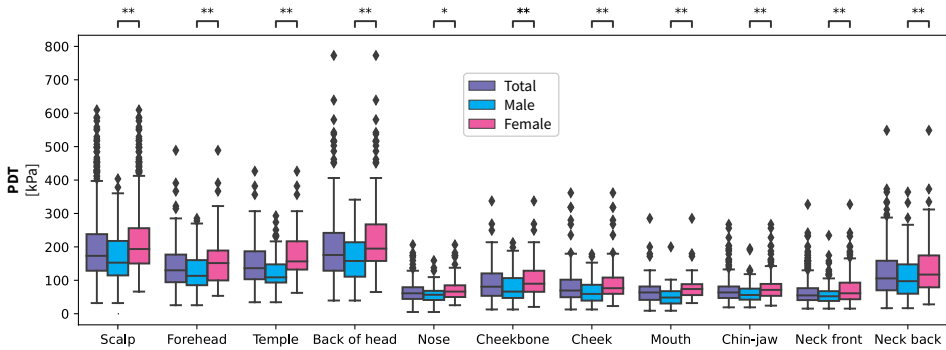


Figure 10.7 | PDT boxplot in kPa of all (n=28), male (n=14) and female (n=14) per zone. Sig.dif. between genders per zone are indicated as * = $p \leq .05$ and ** = $p \leq .01$. Please note that long hair of female participants and the pressure by the headcap may influence gender and zone differences (see also §10.4.2).

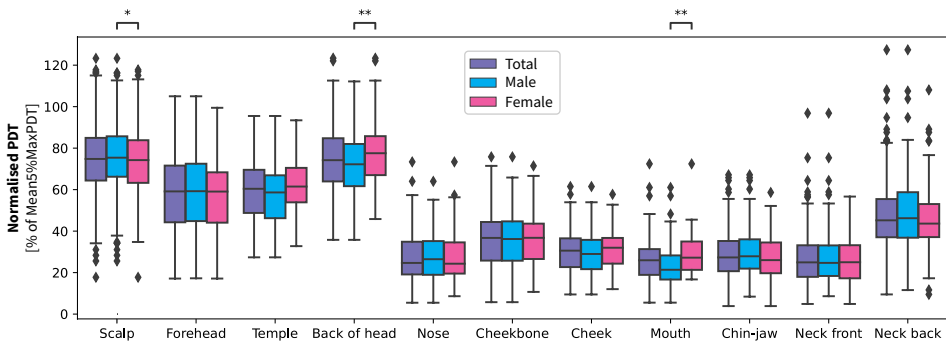


Figure 10.8 | Normalised PDT boxplot of all (n=28), male (n=14) and female (n=14) per zone. Sig.dif. between genders per zone are indicated as * = $p \leq .05$ and ** = $p \leq .01$. Please note that long hair of female participants and the pressure by the headcap may influence gender and zone differences (see also §10.4.2).

10.3.3. PDT zone difference

As shown in Figure 10.4 and Table 10.2 and Table 10.3, a low PDT was found in areas around the *nose*, *neck front*, *mouth*, *chin-jaw*, *cheek* and *cheekbone*. Medium PDT was found in the *neck back*, *forehead*, *temple*, and high PDT in the *back of the head* and *scalp*. The *scalp* and *back of the head*, *forehead* and *temple*, and the *nose*, *cheekbone*, *cheek*,

mouth, chin-jaw and neck front (with a few exceptions) do not significantly differ. Arguably these zones could be treated as one zone (i.e. *parietal-occipital region, frontal-temporal region, face-front-neck region* respectively).

Table 10.2 | Mean (SD) measured PDT (in kPa) of all (n=28), male (n=14) and female (n=14) and gender-based difference per zone per zone. Sig.dif. between genders per zone are indicated as * = $p \leq .05$ and ** = $p \leq .01$. Please note that long hair of female participants and the pressure by the headcap may influence gender and zone differences (see also §10.4.2).

Zone	Measured PDT (in kPa)			
	All mean (SD) (n=28)	Male mean (SD) (n=14)	Female mean (SD) (n=14)	Gender based difference <i>p</i> -value
Scalp	190.7 (83.8)	167.3 (72.8)	214.2 (94.9)	$p \leq .01^{**}$
Forehead	144.1 (69.4)	129.7 (62.9)	158.6 (75.9)	$p \leq .01^{**}$
Temple	151.2 (64.7)	125.2 (56.5)	177.3 (73.0)	$p \leq .01^{**}$
Back of head	196.1 (91.7)	165.4 (72.3)	226.8 (111.1)	$p \leq .01^{**}$
Nose	67.1 (34.2)	59 (28.9)	75.3 (39.6)	$p \leq .05^{*}$
Cheekbone	92 (50.6)	80 (45.4)	104 (55.8)	$p \leq .01^{**}$
Cheek	80.1 (47.9)	66.5 (36.2)	93.8 (59.7)	$p \leq .01^{**}$
Mouth	67.3 (37.9)	53.6 (32.9)	81 (43.0)	$p \leq .01^{**}$
Jaw-chin	70.3 (34.8)	61.1 (27.8)	79.5 (41.8)	$p \leq .01^{**}$
Neck front	65 (35.8)	56.1 (27.1)	73.9 (44.6)	$p \leq .01^{**}$
Neck back	121 (69.8)	108.7 (64.5)	133.3 (75.1)	$p \leq .01^{**}$

Table 10.3 | Mean (SD) normalised PDT of all (n=28), male (n=14) and female (n=14) and gender-based difference per zone per zone. Sig.dif. between genders per zone are indicated as * = $p \leq .05$ and ** = $p \leq .01$. Please note that long hair of female participants and the pressure by the headcap may influence gender and zone differences (see also §10.4.2).

Zone	Normalised PDT (in percentage)			
	All mean (SD) (n=28)	Male mean (SD) (n=14)	Female mean (SD) (n=14)	Gender based difference <i>p</i> -value
Scalp	74.8 (14.8)	75.6 (15.0)	74.1 (14.6)	$p \leq .05^{*}$
Forehead	57.7 (18.7)	58.7 (18.1)	56.6 (19.4)	.42
Temple	59.6 (14.0)	57.7 (15.4)	61.5 (12.4)	.09
Back of head	74.5 (15.1)	72.2 (15.4)	77.0 (14.5)	$p \leq .01^{**}$
Nose	27.5 (12.0)	27.8 (12.0)	27.3 (12.2)	.75
Cheekbone	35.9 (13.4)	35.8 (13.7)	36.0 (13.2)	.96
Cheek	30.5 (10.1)	29.6 (10.7)	31.4 (9.3)	.11
Mouth	26.7 (10.9)	24.5 (11.5)	28.8 (10.0)	$p \leq .01^{**}$
Jaw-chin	28.8 (10.9)	30.2 (11.9)	27.5 (9.7)	.11
Neck front	26.4 (11.4)	26.9 (11.6)	25.8 (11.1)	.45
Neck back	47.0 (17.4)	48.3 (19.4)	45.7 (15.1)	.26

10.4. Discussion

The experiment results show that the *nose*, *neck front*, *mouth*, *chin-jaw*, *cheek* and *cheekbone* areas are most sensitive (low PDT), where the *neck back*, *forehead* and *temple* regions are medium-sensitive (medium PDT), and the *back of the head* and *scalp* are least sensitive (high PDT). This is in line with existing literature. Shah and Luximon (2021) found in Chinese adults (n=218), when investigating the entire head and parts of the neck, that the *facial region* was the most pressure sensitive area, where the *forehead* and *temporal region* were medium, and the *skull area* was least sensitive. Brough and Konz (1992) found in young adults (n=30), when investigating the top part of the head, the *temple area* to be the most sensitive, medium sensitive was the *inferior frontal area* and the *parietal region*, and least sensitive was the *superior frontal area* and *occipital region*. Broekhuizen et al. (2019) (n=19), who also investigated the top part of the head, found the *inferior frontal area* to be most sensitive, medium sensitive in the *temple region*, *parietal eminence region*, *superior frontal* and *parietal region*, and least sensitive in the *superior occipital* and *inferior occipital region*. Franz et al. (2012) (n=46) found that the *neck* was more sensitive than the *back of the head*.

When reanalysing the reported data by Broekhuizen et al. (2019) and Shah and Luximon (2021), by taking the mean of all landmarks within each zone as defined in this study, one can see a similar trend of pressure distribution on the head, face and neck (see Figure 10.9). Noticeable is that the pressure values of Shah and Luximon (2021) are double of those of Broekhuizen et al. (2019) and this study. A possible explanation is the difference in probe used (Goonetilleke & Eng, 1994) or ethnicity of the tested populations (Komiya, Kawara, & De Laat, 2007). Where Broekhuizen et al. (2019) used a $\varnothing 11.3$ mm probe on a European population, Shah and Luximon (2021) used a $\varnothing 3$ mm on a Chinese population and this study $\varnothing 10$ mm on an International – but predominantly European – population.

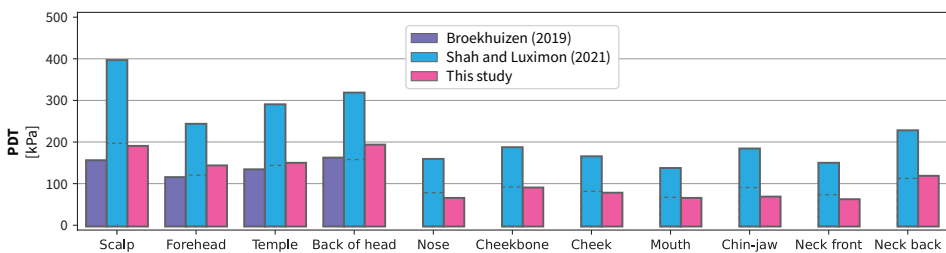


Figure 10.9 | Mean PDT per zone in kPa for Broekhuizen et al. (2019) (n=19), Shah and Luximon (2021) (n=218) and this study (n=28).

Previous studies use fixed anatomical landmarks. This method allows for easier analysis, but limits landmark density (as clear anatomical landmarks are missing on undistinctive surfaces like the *cheeks*, *forehead*, *scalp* and *neck*, making accurate landmark placement difficult) and thereby model accuracy. This study introduces a new method, which allows for a dense landmark coverage without the need of anatomical

landmarks. This method uses the 3D location of each landmark to make a comparison between participants, and a PDT map by means of interpolation possible. The benefit of using 3D scanning to capture landmark locations is that it is more precise and allows for freedom of placement of landmarks.

The sparsity of anatomical landmarks in previous studies leads to a rough estimation of PDT in regions sparse of landmarks. The higher landmark density introduced in this study on head, face and neck PDT results in a more precise and detailed map. For example, comparing this study's results with that of Broekhuizen et al. (2019) and Shah and Luximon (2021) for the region above the eyebrows, shows that this study's PDT map is more accurately defined due to a denser probing of that area. Such finer PDT details could help designers and engineers to adjust their design to interface with less sensitive areas and spare sensitive areas.

10.4.1. Underlying tissue

The difference in PDT per area could be explained by the underlying tissue, such as skin thickness and underlying fat tissue, muscles, nerves, blood veins, cartilage, and bone. It could also be influenced by receptor density. For instance, in the cheek and nose receptors are more proximate to each other than in the forehead (Corniani & Saal, 2020). In areas with excess subcutaneous fat, people are less sensitive (Price, Asenjo, Christou, Backman, & Schweinhardt, 2013). However, Shah and Luximon (2021) found that PDT of the head was independent of BMI.

That said, regions with a high density of receptors like the nose (*nasal region*) and area around the mouth (*oral region*) show a low PDT. As do areas with arteries like the *temple* and *front neck*, where the latter also contains critical soft tissue like the *trachea* and *oesophagus*. Also noticeable is the sensitivity around the eyes (*orbital region*), and especially above the eye at the eyebrows and lower part of the forehead (*inferior frontal region*). Possibly these zones are extra sensitive in order to protect one of our most dominant and vulnerable sensory organs: the eyes. Tissue proximate to bone like the *cheekbone*, *chin* and *scalp* are less sensitive than their proximate regions with more underlying soft tissue. The big exception here is the *back of the neck*, possibly due to the high density of strong muscle tissue.

10.4.2. Differences between genders

Fischer (1987) found that females had a lower PDT/PPT than men at the lower and upper back and shoulders. Antonaci et al. (1992) found no significant differences in PPT between genders, where Jensen, Rasmussen, Pedersen, Lous, and Olesen (1992) also found that females had a lower PPT than men. Hung and Samman (2009) found a higher pain detection threshold in males, especially in the chin and the right infraorbital areas. K. H. Lee, Lee, Kim, Kim, and Chung (1994) found no definitive correlation between PPT and gender, but found that PPT in the head and neck muscles were generally lower in women than in men. Stefani et al. (2012) found a lower PPT in females at the mid-forearm, but gender influence was not statistically significant. Melia et al. (2019) found that men, as

well as manual labourers, had comparatively higher adjusted PPT in the *forehead*, *temple*, *m. masseter* and *m. sternocleidomastoid* than females. Broekhuizen et al. (2019) found that women had a lower PDT than males on the whole head (*frontal*, *parietal*, *temporal* and *occipital regions*). Shah and Luximon (2021) found that females had a lower PDT than males in two-third of their 76 landmarks on the head, face and neck.

Opposite to most literature, this study's results indicate that women are – based on absolute PDT values – less sensitive than men (higher PDT), especially on the *scalp*. Normalised PDT values (based on the Mean5%MaxPDT) of each landmark within each zone for males and females only significantly differ on the *scalp*, *back of the head* and *mouth*, indicating that PDT is similarly distributed in males and females for the other zones. This is an important insight, as it indicates no gender deviating product-human interface distribution is needed. However, gender difference in absolute pressure tolerance should possibly be considered in product-human interface design.

A possible explanation for the found absolute pressure difference could be that the female participants had long hair, which – although put in a knot to the side to minimise hair between cap and skin – could have damped and spread the applied pressure. E.g. the results of Myles, Kalb, Lowery, and Kattel (2015) suggest that hair density might slightly impede vibration signals from reaching the scalp and reduce vibration sensitivity, for the least sensitive locations on the head. Also hair thickness (fine, medium and coarse) and type (straight, curly) could play a role, as suggested – but not investigated – by Brough and Konz (1992). Another explanation could be the constant pull of long hair to the skin, making these females used to a certain amount of (tension) force on their scalp skin, resulting in other PDT's.

10.4.3. Design implications

The use of a 3D head, face and neck PDT map could help designers and engineers create better and more comfortable products interfacing with the head, face and neck, e.g. by mounting equipment on and interface between human and product on less sensitive areas. Meanwhile, the PDT map can also contribute to the design of medical devices, e.g. as an indication to prevent medical device related pressure ulcers (Black et al., 2015; Gefen et al., 2020), and as a threshold of discomfort in applying diagnostics tools/physical interventions (Posnick et al., 1990).

Vink and Lips (2017) found low PDT in the buttocks, where Zenk, Franz, Bubb, and Vink (2012) found that long-term discomfort (> 2 h) was weaker in the buttocks than in the knee cavities. This suggests that PDT can indicate long-term discomfort effects. Arguably, the present study results could thus be used for designing equipment which prolongedly interfaces with the head, face and neck. Keeping in mind that using a tool like this head, face and neck PDT map, always requires considered decision making by designers and engineers (Hiemstra-van Mastrigt, Smulders, Bouwens, and Vink (2019); see Chapter 1).

However, long-term contact – which can cause besides pressure also shear force, and isolation of heat and moisture/sweat – may lead to discomfort in the long run, or can even lead to rashes, swelling, ulcers or sores (Bhattacharya & Mishra, 2015; Gefen et al., 2020; Goossens, 2009; Goossens, Zegers, van Dijke, & Snijders, 1994; Singh et al., 2020). This is of specific importance in e.g. medical contexts, where patient impaired sensory perception or impaired ability to communicate discomfort can lead to medical device related pressure ulcers (Black et al., 2015; Gefen et al., 2020).

To aid designers and engineers e.g. in CAD, the average PDT was mapped to a statistical shape model (SSM) of the human head, developed on the CAESAR 3D Anthropometric Database (Robinette, Blackwell, Daanen, Boehmer, & Fleming, 2002) (see Figure 10.10). While the PDT on different geometric heads is available, it is an approximation using the mean PDT data ($n=28$) and may not be as representative for the respective populations they are mapped upon. Future works could be directed toward collecting a larger dataset on PDT as well as 3D shapes of the head/neck and the associated parameters. Based on this dataset a 4D multimodality SSM can be built to approximate PDTs for individuals within the population, and to identify which variables (e.g. shape, soft tissue thickness, gender, culture, ethnicity, etc.), if any, can explain intersubject variability of PDT.

10.4.4. Limitations and suggestions for further research

The 3D PDT map of the head, face and neck only gives an indication of (dis)comfort (sensitivity), as shear force, cutting of (micro-vein) blood flow and moisture (e.g. sweat) obstruction by loads of head, face and neck related equipment are not investigated. The map is also based on an internationally mixed sample of $n=28$. Although the sample size is relatively comparable to previous studies (e.g. Antonaci et al. (1992), Broekhuizen et al. (2019) and Brough and Konz (1992)), a larger sample size like Shah and Luximon (2021) could result in a more representative PDT map.

Also investigation of to what extent the PDT maps are comparable between ethnicities could be considered, as Ball et al. (2010) showed a significant difference in head shapes between Chinese and Caucasian, and Komiyama et al. (2007) found a difference in tactile and pain thresholds between Belgians and Japanese. Besides physical differences, cultural difference could influence (dis)comfort evaluations as well (Vink et al., 2021). When comparing Broekhuizen et al. (2019) and this study with Shah and Luximon (2021), differences can be seen (see Figure 10.9), although probe size could of be influence here as well.

This study limits between-subject variability by means of normalisation based on the 5%MaxPDT, to limit the effect of outliers on the normalisation. That said, this normalisation method is based on subjective ratings. A maximal tolerated pressure test is more commonly used for normalisation (e.g. in EMG studies), but is not recommendable in a PDT study, as participants may go too far and exceed safe pressure limits. Normalisation based on a fixed pressure (e.g. 20, 50 and 80 kPa) on a fixed landmark (e.g. *philtrum*, *alare*, *sellion*, *tragion* and *glabella*) would not be a valid alternative, as it introduces another subjective scale. Future studies might consider

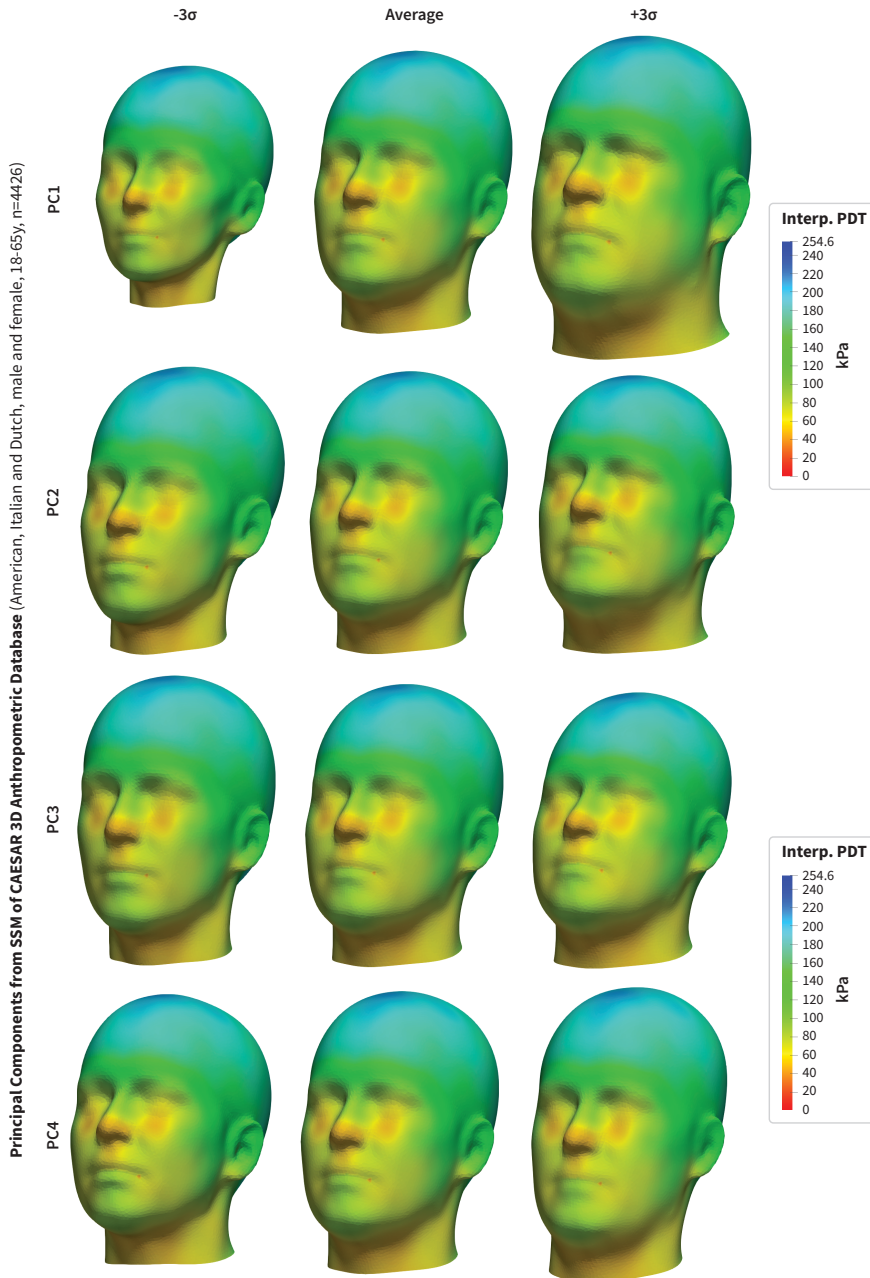


Figure 10.10 | Average PDT (based on n=28 sample from this study) mapped on the human head SSM (from Principal Component 1 to PC4, $\pm 3\sigma$) built on the CAESAR 3D Anthropometric Database (USA, Italy and The Netherlands, male and female, 18-65y, n=4309), isometric view. Please note that shading is on to improve depth perception, which may affect colour (and thus PDT value) interpretation. The use of the digital models is advised, which extends till PC50 (please see the *open data access* section at §10.6).

physiological signals for objectification and normalisation of PDT (e.g. muscle contraction (EMG) or heartrate (ECG)) (e.g. Yang, Chen, He, Goossens, and Huysmans (2024)).

Although this study has a high landmark density, the used landmark distance in this study (appr. 2–3 cm) can still be ‘*too big*’ to find subtle differences. Future work might want to investigate zones of interest in more detail, e.g. on and around the eyes, nose, ears and mouth for e.g. goggles, headphones and masks.

Although the landmarks were passed in a random order and successive stimulation of proximate landmarks were not noted, rare successive stimulation of adjacent landmarks without a sufficient interval might have influenced the PDT readings between them. For future studies, a randomiser which prevents successive stimulation of proximate landmarks is therefore recommended. Another limitation is the potential order effect of going through positions A,B and C sequentially. In position B the participant lies with their face down on the massage seat and thus experience some pressure on the face. This could have impacted the experienced PDT in position C. It is recommended to also randomise the order of taking positions A, B and C.

In addition, further research on the validity of short-term discomfort indication on actual experienced long-term comfort is needed, as is the evaluation of usability of the head, face and neck PDT map in product design. Also, the relation of PDT and underlying tissue could be investigated in more depth, e.g. from a medical, biomechanical and/or anatomical perspective. Capturing PDT data via an automated process (e.g. like Shah and Luximon (2021)) is advised, to save on time and staff in future research.

10.5. Conclusion

A dense 3D pressure discomfort threshold (PDT) map of the human head, face and neck was made based on 126–146 left-lateral landmark locations in 28 participants (international, but majority European Caucasian, population). In comparison with previous studies, this study introduces a more landmark-dense, and therefore arguably a more detailed PDT map of the human head, face and neck. This study also introduces a new method where pressure discomfort threshold data is combined with 3D landmark locations, which are not limited to anatomically identifiable locations, allowing for more precision and freedom in placement of landmarks.

Results indicated that the *nose*, *neck front*, *mouth*, *chin-jaw*, *cheek* and *cheekbone* regions can tolerate the lowest pressure, where the *neck back*, *forehead* and *temple* regions are medium and the *back of the head* and *scalp* have the most tolerance, which is in line with existing literature.

This study also found that females have higher PDT levels than males in all regions, where most literature indicates the opposite. Further research on long-term pressure (dis)comfort and usability of this 3D PDT map are needed.

10.6. Open data access

The 3D PDT maps (incl. PDT mapped on the SSM of the human head developed on the CAESAR 3D Anthropometric Database), average 3D head model and PDT data are available at data.4tu.nl (doi.org/10.4121/21482328) under CC BY-SA 4.0 licence. For privacy reasons, landmark coordinates and 3D scan mesh data of individual participants are not made available.

Please cite this publication when making use of the model and/or the data set. Users of the PDT maps are encouraged to share their experiences with the authors (e.g. via forum.dined.nl).

10.7. Ethical approval

This study was approved by the Delft University of Technology *Human Research Ethical Committee* (hrec.tudelft.nl) on 18 July 2019 (approval no. 772), in accordance with The Helsinki Declaration (World Medical Association, 2013). Research materials and method, including a ‘*sticker allergic reaction test*’, were evaluated with a medical doctor and approved by a *Health, Safety and Environment Officer* of the Delft University of Technology.

Participants recognisable on pictures and 3D scans gave explicit permission to be recognisable in this publication. Other models are maps on a generic head model made of merging all 3D scans of all participants into one.

10.8. Declaration of competing interest

This study was a collaboration between Crescent Medical B.V. and the Delft University of Technology in 2019-2020. Crescent Medical contributed to this study in manpower. Study set-up and execution were in collaboration with Crescent Medical, but Crescent Medical was not involved in, nor had influence on the analysis and creation of the 3D PDT maps. Crescent Medical had early access to the 3D PDT maps for designing a surgical headset, before making the maps accessible to the public in 2022.

10.9. Acknowledgements

We want to thank miss L. Di Brigida and mr. B.J. Naagen for their assistance in conducting this study. We also want to thank E. Heesterbeek-Verburg (MD) for medical safety consulting, and dr. T. Albin for his advice on statistics. We thank Crescent Med, in particular ir. S.R. Andary, for supporting this study by making manhours available. This study was partly financed by the Dutch Research Council (NWO) (project number: 18636).

The authors would also like to acknowledge the previous unpublished work of our MSc. students on sensitivity of different features of the head for a multitude of design projects, as their work showed the need and laid the groundwork for a full head PDT model: B. Bossenbroek, J. van Dijk, L. Kok, T. Paclik, J. Snoek, G. van Soelen; T.A. Rotte, M. Otten, Z.M. Hayde, V. Aus dem Kamen, P. Möisinger, J.E. Sanchez; S. Krabbenborg, A. Bisnajak, A. Abarca, E. Liermann, P. Bosch and N. van den Brink.

And last but not least we would like to thank all the volunteers who were so kind to take part in this study.

10.10. References

- Antonaci, F., Bovim, G., Fasano, M., Bonamico, L., & Shen, J. (1992). Pain threshold in humans. A study with the pressure algometer. *Funct Neurol*, 7(4), 283-288.
- Ball, R., Shu, C., Xi, P., Rioux, M., Luximon, Y., & Molenbroek, J.F.M. (2010). A comparison between Chinese and Caucasian head shapes. *Applied ergonomics*, 41(6), 832-839. doi:10.1016/j.apergo.2010.02.002
- Bhattacharya, S., & Mishra, R. (2015). Pressure ulcers: current understanding and newer modalities of treatment. *Indian Journal of plastic surgery*, 48(01), 004-016. doi:10.4103/0970-0358.155260
- Black, J., Alves, P., Brindle, C.T., Dealey, C., Santamaria, N., Call, E., & Clark, M. (2015). Use of wound dressings to enhance prevention of pressure ulcers caused by medical devices. *International wound journal*, 12(3), 322-327. doi:10.1111/iwj.12111
- Broekhuizen, R., De Rydt, T., Lutters, E., Ten Klooster, R., & De Bruyne, G. (2019). Head Sensitivity for Designing Bicycle Helmets with Improved Physical Comfort. Paper presented at the International Conference on Applied Human Factors and Ergonomics. doi:10.1007/978-3-319-94706-8_2
- Brough, P., & Konz, S. (1992). Pressure sensitivity of the head. Paper presented at the Annual International Industrial Ergonomics and Safety Conference, Denver, Colorado, USA.
- Buso, A., & Shitoot, N. (2019). Sensitivity of the foot in the flat and toe off positions. *Applied ergonomics*, 76, 57-63. doi:10.1016/j.apergo.2018.12.001
- Corniani, G., & Saal, H.P. (2020). Tactile innervation densities across the whole body. *Journal of Neurophysiology*, 124(4), 1229-1240. doi:10.1152/jn.00313.2020
- Dyke, R.M., Lai, Y.-K., Rosin, P.L., Zappalà, S., Dykes, S., Guo, D., . . . Yang, J. (2020). Shrec'20: Shape correspondence with non-isometric deformations. *Computers & Graphics*, 92, 28-43. doi:10.1016/j.cag.2020.08.008
- Fenko, A., Schifferstein, H.N., & Hekkert, P. (2010). Shifts in sensory dominance between various stages of user-product interactions. *Applied ergonomics*, 41(1), 34-40. doi:10.1016/j.apergo.2009.03.007
- Fischer, A.A. (1986). Pressure threshold meter: its use for quantification of tender spots. *Archives of physical medicine and rehabilitation*, 67(11), 836-838.
- Fischer, A.A. (1987). Pressure algometry over normal muscles. Standard values, validity and reproducibility of pressure threshold. *Pain*, 30(1), 115-126. doi:10.1016/0304-3959(87)90089-3
- Fransson-Hall, C., & Kilbom, Å. (1993). Sensitivity of the hand to surface pressure. *Applied ergonomics*, 24(3), 181-189. doi:10.1016/0003-6870(93)90006-u
- Franz, M., Durt, A., Zenk, R., & Desmet, P.M.A. (2012). Comfort effects of a new car headrest with neck support. *Applied ergonomics*, 43(2), 336-343. doi:10.1016/j.apergo.2011.06.009

- Gefen, A., Alves, P., Ciprandi, G., Coyer, F., Milne, C.T., Ousey, K., . . . Worsley, P. (2020). Device-related pressure ulcers: SECURE prevention. *Journal of Wound Care*, 29(Sup2a), S1-S52. doi:10.12968/jowc.2020.29.5.245
- Goonetilleke, R.S., & Eng, T.J. (1994). Contact area effects on discomfort. Paper presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting. doi:10.1177/154193129403801032
- Goossens, R.H.M. (2009). Fundamentals of Pressure, Shear and Friction and Their Effects on the Human Body at Supported Postures. In A. Gefen (Ed.), *Bioengineering Research of Chronic Wounds: A Multidisciplinary Study Approach* (pp. 1-30). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-642-00534-3_1
- Goossens, R.H.M., Zegers, R., van Dijke, G.H., & Snijders, C. (1994). Influence of shear on skin oxygen tension. *Clinical physiology*, 14(1), 111-118. doi:10.1111/j.1475-097x.1994.tb00495.x
- Gower, J.C. (1975). Generalized procrustes analysis. *Psychometrika*, 40(1), 33-51. doi:10.4135/9781412952644.n186
- Hiemstra-van Mastrikt, S., Smulders, M., Bouwens, J.M.A., & Vink, P. (2019). Designing aircraft seats to fit the human body contour. In *DHM and Posturography* (pp. 781-789): Elsevier. doi:10.1016/b978-0-12-816713-7.00061-1
- Hung, J., & Samman, N. (2009). Facial skin sensibility in a young healthy Chinese population. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology*, 107(6), 776-781. doi:10.1016/j.tripleo.2008.10.026
- Huysmans, T., Goto, L., Molenbroek, J.F.M., & Goossens, R.H.M. (2020). DINED Mannequin. *Tijdschrift voor Human Factors*, 45(1), 4-7.
- Jasper, H.H. (1958). Report of the committee on methods of clinical examination in electroencephalography: 1957. *Electroencephalography and Clinical Neurophysiology*, 10(2), 370-375. doi:10.1016/0013-4694(58)90053-1
- Jensen, R., Rasmussen, B.K., Pedersen, B., Lous, I., & Olesen, J. (1992). Cephalic muscle tenderness and pressure pain threshold in a general population. *Pain*, 48(2), 197-203. doi:10.1016/0304-3959(92)90059-k
- Komiyama, O., Kawara, M., & De Laat, A. (2007). Ethnic differences regarding tactile and pain thresholds in the trigeminal region. *The Journal of Pain*, 8(4), 363-369. doi:10.1016/j.jpain.2006.12.002
- Lee, K.H., Lee, M.H., Kim, H.S., Kim, J.H., & Chung, S.C. (1994). Pressure pain thresholds [PPT] of head and neck muscles in a normal population. *Journal of Musculoskeletal Pain*, 2(4), 67-81. doi:10.1300/j094v02n04_06
- Lee, W., Kim, J.G., Molenbroek, J.F.M., Goossens, R.H.M., & You, H. (2019). Estimation of facial contact pressure based on finite element analysis. Paper presented at the International Conference on Applied Human Factors and Ergonomics. doi:10.1007/978-3-030-20216-3_61

- Melia, M., Geissler, B., König, J., Ottersbach, H.J., Umbreit, M., Letzel, S., & Muttray, A. (2019). Pressure pain thresholds: subject factors and the meaning of peak pressures. *European Journal of Pain*, 23(1), 167-182. doi:10.1002/ejp.1298
- Mergl, C. (2006). Entwicklung eines verfahrens zur optimierung des sitzkomforts auf Automobilsitzen. (Doctoral dissertation), Technische Universität München, München, Germany. Retrieved from <http://mediatum.ub.tum.de/?id=601975>
- Myles, K., Kalb, J.T., Lowery, J., & Kattel, B.P. (2015). The effect of hair density on the coupling between the tactor and the skin of the human head. *Applied ergonomics*, 48, 177-185. doi:10.1016/j.apergo.2014.11.007
- O'Hora, L., Robbins, E., Savidge, L., Tokarick, B., Wood, B., & Holbein-Jenny, M.A. (n.d.). Pain Pressure Threshold (PPT). Retrieved from www.apta.org/patient-care/evidence-based-practice-resources/test-measures/pain-pressure-threshold-ppt
- Oostendorp, T.F., van Oosterom, A., & Huiskamp, G. (1989). Interpolation on a triangulated 3D surface. *Journal of Computational Physics*, 80(2), 331-343. doi:10.1016/0021-9991(89)90103-4
- Parsons, K. (2003). *Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort and performance*: CRC press. doi:10.1201/9781420025248
- Posnick, J.C., Zimble, A.G., & Grossman, J. (1990). Normal cutaneous sensibility of the face. *Plastic and Reconstructive Surgery*, 86(3), 429-433; discussion 434. doi:10.1097/00006534-199009000-00006
- Price, R., Asenjo, J., Christou, N., Backman, S., & Schweinhardt, P. (2013). The role of excess subcutaneous fat in pain and sensory sensitivity in obesity. *European Journal of Pain*, 17(9), 1316-1326. doi:10.1002/j.1532-2149.2013.00315.x
- Ramot, Y., Haim-Zada, M., Domb, A.J., & Nyska, A. (2016). Biocompatibility and safety of PLA and its copolymers. *Advanced drug delivery reviews*, 107, 153-162. doi:10.1016/j.addr.2016.03.012
- Robinette, K.M., Blackwell, S., Daanen, H., Boehmer, M., & Fleming, S. (2002). Civilian american and european surface anthropometry resource (caesar), final report. volume 1. summary. Retrieved from <https://www.humanics-es.com/CAESARvol1.pdf>
- Shah, P.B., & Luximon, Y. (2021). Assessment of pressure sensitivity in the head region for Chinese adults. *Applied ergonomics*, 97, 103548. doi:10.1016/j.apergo.2021.103548
- Shah, P.B., Luximon, Y., & Luximon, A. (2017). Use of soft tissue properties for ergonomic product design. Paper presented at the International Conference on Applied Human Factors and Ergonomics. doi:10.1007/978-3-319-60825-9_19
- Singh, M., Pawar, M., Bothra, A., Maheshwari, A., Dubey, V., Tiwari, A., & Kelati, A. (2020). Personal protective equipment induced facial dermatoses in healthcare workers managing Coronavirus disease 2019. *Journal of the European Academy of Dermatology and Venereology*. doi:10.1111/jdv.16628

- Stefani, L.C., da Silva Torres, I.L., De Souza, I.C.C., Rozisky, J.R., Fregni, F., & Caumo, W. (2012). BDNF as an effect modifier for gender effects on pain thresholds in healthy subjects. *Neuroscience letters*, 514(1), 62-66. doi:10.1016/j.neulet.2012.02.057
- Vink, P., Anjani, S., Udomboonyanupap, S., Torkashvand, G., Albin, T., Miguez, S., . . . Vanacore, A. (2021). Differences and similarities in comfort and discomfort experience in nine countries in Asia, the Americas and Europe. *Ergonomics*, 64(5), 553-570. doi:10.1080/00140139.2020.1853248
- Vink, P., & Hallbeck, S. (2012). Editorial: Comfort and discomfort studies demonstrate the need for a new model. *Applied ergonomics*, 43(2), 271-276. doi:10.1016/j.apergo.2011.06.001
- Vink, P., & Lips, D. (2017). Sensitivity of the human back and buttocks: The missing link in comfort seat design. *Applied ergonomics*, 58, 287-292. doi:10.1016/j.apergo.2016.07.004
- World Medical Association. (2013). World Medical Association Declaration of Helsinki: Ethical Principles for Medical Research Involving Human Subjects. *JAMA*, 310(20), 2191-2194. doi:10.1001/jama.2013.281053
- Xiong, S., Goonetilleke, R.S., & Jiang, Z. (2011). Pressure thresholds of the human foot: measurement reliability and effects of stimulus characteristics. *Ergonomics*, 54(3), 282-293. doi:10.1080/00140139.2011.552736
- Yang, W., Chen, T., He, R., Goossens, R., & Huysmans, T. (2024). Autonomic responses to pressure sensitivity of head, face and neck: Heart rate and skin conductance. *Applied ergonomics*, 114, 104126. doi:10.1016/j.apergo.2023.104126
- Zenk, R., Franz, M., Bubb, H., & Vink, P. (2012). Spine loading in automotive seating. *Applied ergonomics*, 43(2), 290-295. doi:10.1016/j.apergo.2011.06.004
- Zenk, R., Mergl, C., Hartung, J., Sabbah, O., & Bubb, H. (2006). Objectifying the comfort of car seats. *SAE Conference 2006*. doi:10.4271/2006-01-1299
- Zhuang, Z., & Bradtmiller, B. (2005). Head-and-face anthropometric survey of US respirator users. *Journal of occupational and environmental hygiene*, 2(11), 567-576. doi:10.1080/15459620500324727

GENERAL DISCUSSION AND CONCLUSION RECOMMENDATIONS FOR RESEARCH AND DESIGN

The aim of the dissertation was to provide background information, design guidelines and suggestions for designers and engineers to aid them in designing comfortable and useful seating and sleeping environments in vehicles like trains, aircraft, (autonomous) cars, ships and submarines. This chapter contains an overview of the results of the studies, a reflection on the focus, suggestions for future scientific research and recommendations for industry on vehicle interior research and design.

11.1. Overview of the results linked to the research questions

Research question 1 “*How does human behaviour and time impact comfort?*” was discussed in Part 1, which shows that it is important in (dis)comfort research to indicate what participants did before participating in the test (prior activities), how they move/behave during the test, what postures they assume, whether there are stimuli used that distract or influence the behaviour, and whether participants are aware of time or the end/duration of activities/stimuli (Chapter 2). It also shows how time impacts the (dis)comfort experience, where discomfort tends to stabilise or decrease and comfort tends to stabilise or increase towards the end, possibly because participants have the idea that relief is coming (Chapter 3). Therefore, researchers should know that in experiments participants being aware of time may impact their (dis)comfort rating.

Research question 2 “*How to design a seat based on the human contour?*” was studied in Part 2, which shows a methodology based on 3D scanning to design seats based on the human contour (Chapter 4 and 5). A human contoured seat does have similar or better (dis)comfort scores compared to a traditional seat (Chapter 4 and 6). Additionally, the increased surface contact results in an all-over better distributed (in line with Mergl (2006)) pressure distribution (Chapter 6). It also opens possibilities to reduce seat weight and seat volume, which was shown for a business class, premium economy, and economy class aircraft seat (Chapter 4 and 5). Franz, Kamp, et al. (2011) showed that weight reduction and comfort increase is also possible for car seats using 3D scans of the human body. This section also shows that the combination of optimisation of pressure distribution, the use of porous materials (e.g. weaved meshes (Chapter 4) or foam spring (Chapter 6)) and topology optimised structures can reduce weight and at the same time increase comfort. Keeping a similar or more favourable comfort rating and a lower weight is beneficial to reduce environmental impact, which is relevant for future vehicle interior design as discussed in the introduction. Although this section provides a methodology for designing a seat based on the human contour, further research and development on the ‘ideal’ human contour is needed (see §11.3).

A start was made on answering research question 3 “*How to improve sleep quality in full-flat sleeping in transit within minimal space?*” in Part 3, which shows that healthy people need to be able to freely move during sleep, and that limiting space influences sleep quality, efficiency and comfort. Although lateral and supine postures are dominant (Chapter 7), in-vehicle bed-seat designs should allow for postural changes and micromovements to facilitate natural sleep behaviour (Haex, 2004). The sleeping space envelope can be reduced, but negatively impacts sleep quality and comfort. This dissertation shows that with a space reduction of ~25% the sleep quality, efficiency and comfort is less, but not significantly different than sleeping in one’s own bed despite the space reduction, where sleeping in a 30% space reduced bed resulted in significant lower sleep quality, efficiency and comfort (Chapter 8). However, it is up to designers and engineers to consciously balance the sleep space envelope and sleep quality, efficiency, and comfort against other requirements like economics and operational safety. Further research is needed to adequately answer this research question (see §11.3-4).

Research question 4 “*How to improve reclined watching IVE in transit by means of a headrest?*” was discussed in Part 4, which shows that headrest support for watching IFE in a reclined posture (which is preferred over upright sitting for this activity) does not lower muscle activity (based on EMG), but benefits (expected) user comfort (Chapter 9). Also, a methodology was developed to create a head pressure sensitivity model, which can be used in designing a multitude of head, neck and face interfacing products (Chapter 10). In this doctoral dissertation this is relevant in the context of headrest design; providing support for watching IFE and reclined sleeping. High pressures by a headrest should be avoided around the ear, temple and neck area, whereas most of the load can be carried by the back of the head and the jaw line. Franz, Durt, Zenk, and Desmet (2012) already showed that the neck is more sensitive. However, in the study of this doctoral dissertation the number of measuring points in the neck is much higher and covers the entire head, enabling a more precise softer area definition and provides information for e.g. side bolster design (with soft ear/temple area and firmer jaw area for support) for lateral head support for reclined sleeping. Although this section shows that head support could be beneficial and the head sensitivity model provides a starting point for developing headrests for watching IVE, further research on headrest design for IVE is needed to adequately answer this research question (see §11.3 and §11.4). Especially for headrest design for reclined sleeping (see §11.4.2.3-4).

The main research question of this doctoral dissertation was “*What are the physical ergonomic factors that influence seating comfort, relaxing comfort and sleeping quality and comfort?*” The studies published in this doctoral dissertation show that physical factors have influence on seating, relaxing and sleeping comfort and quality. In general, the cases in this doctoral dissertation show that taking the human contour, the human (pressure) sensitivity, human behaviour, in-seat/cabin activities and time into account can support in designing more comfortable, effective and potentially safer seating and sleeping environments in vehicles. Existing literature, as discussed in the chapters, support these conclusions. In many cases, relevant environments and conditions need to be studied in more detail in order to provide more substantiated and detailed guidelines for industry and science (see §11.3). Based on studies that were originally intended for this PhD (e.g. study the effects of reclined sleeping and headrest design for reclined sleeping; see §11.4.2.3-4) and/or insights gained during this PhD, additional recommendations for further research on comfortable seating and sleeping in vehicles can be given (see §11.4). Based on insights from this dissertation, initial recommendations can be given for industry on comfortable seat and sleep design in vehicles (see §11.5).

11.2. Reflection on focus and methodology

The intention of this PhD was originally to expand from seating and elaborate on sleeping in transit, with a focus on physical ergonomic dimensions impacting sleep quality, efficiency and comfort for both full-flat and reclined (upright) sleeping, as knowledge on this field is limited. In the process towards obtaining a PhD, assistance was provided to Master students, other PhD candidates and university- and company researchers, and other projects were initiated. Although connected, these projects deviated from the original main topic of this PhD and consumed the majority of time. These projects were interesting and valuable to share in the scientific domain by means of publications and to incorporate in this doctoral dissertation. This is why the scope of this PhD was broadened. Reflecting on this, it is recommended to researchers, and new PhD candidates in particular, to keep the focus on the original subject. Although interesting opportunities may cross your path, linked to the main topic, they may consume time needed for your own research.

On the other hand, these deviations led to interesting collaborations, new and relevant knowledge, building a network and making writing a doctoral dissertation a less isolated path. It also allows for sharing methods and information with others, develop new methods and learn from others. Where a focussed but isolated PhD may have resulted in a more focussed dissertation, it possibly would not have led to the amount of new knowledge through synergies developed between researchers and collaborators.

Also, the COVID-19 pandemic severely impacted the PhD planning, and postponed access to Polysomnography (PSG) education and access to physical experiments with participants. It might have been beneficial for this PhD to do the sleep research earlier and to have had more possibilities of research with participants to strengthen the sleep quality outcomes and to have more empirical evidence.

Many methods were used (or further developed, see Chapter 10) in this PhD (see Table 11.1), which helped to create theoretical insights in the field of comfort. The used methods can be divided in objective and subjective measurements (predominantly questionnaires).

11.2.1. Objective methods

Activity observations in this PhD provided insight on behaviour and postures of participants conducting frequently performed activities in seats, which were used to determine seat recline configurations (e.g. active, relaxed and sleeping activities) (Chapter 4 and 9) and space envelopes to support these activities (Chapter 7 and 8). Anthropometric measurements gave background information on the range of representation of the sampled population and input for product measurements and adjustability (Chapters 4-6, 8-10). 3D scanning and modelling were used to capture the human contour in various seated positions to design a seat based on the human contour (Chapter 4 and 5) and to capture landmark coordinates for a pressure discomfort threshold map of the human face, neck and head (Chapter 10).

Pressure mapping was used to optimise pressure distributions based on Mergl (2006) and Zenk (2008) in prototype seats and to understand the impact of human contoured seat designs on pressure distribution (Chapter 4 and 6). Pressure discomfort threshold (PDT) analysis gave insights into where and with what firmness on the human head, neck and face products (e.g. headrests) should ideally interface to provide comfortable support. Biomechanical model simulation in AnyBody™ was used to predict muscle activity in different head-neck positions when watching IFE/IVE in a reclined posture (Chapter 9). EMG was used to evaluate the impact of a headrest for watching IFE/IVE on muscle activity (Chapter 9).

11.2.2. Subjective methods

To gain initial insight on performed in-flight activities, their duration and rated importance, interviews were informative for focussing the research (Chapter 4). As (dis)comfort is a subjective phenomenon (Vink, 2004), many studies in this doctoral dissertation used (dis)comfort questionnaires (Anjani et al., 2021) (Chapter 2-4, 6, 8, 9). To measure sleep quality and sleep efficiency, standardised and validated questionnaires were used, like the Pittsburg Sleep Quality Index (PSQI) (Buysse, Reynolds III, Monk, Berman, & Kupfer, 1989), the Karolinska Sleepiness Scale (KSS) (Åkerstedt & Gillberg, 1990; Kaida et al., 2006) and the Samn-Perelli 7-point Fatigue Scale (SPFS) (Samn & Perelli, 1982) (Chapter 8).

Table 11.1 | Methods used in this dissertation

Method	Chapter in dissertation
Observations	2 ^a , 4, 7 ^a , 8, 9
Posture analysis	2 ^b , 4, 7 ^c , 8 ^c , 9
Anthropometric measurements	4-6, 8-10
3D scanning	4, 5, 10
Pressure mapping	4, 6
Pressure discomfort threshold (PDT) mapping	10
Biomechanical model simulation (AnyBody™)	9
Electromyography (EMG)	9
Systematic literature review	7
Interviews	4
Likert scale (dis)comfort questionnaires (Anjani et al., 2021; Joshi, Kale, Chandel, & Pal, 2015)	2 ^a , 3 ^a , 4, 6, 8
Visual Analog discomfort Scale (VAS) questionnaires	3 ^a , 9
Local Perceived Discomfort (LPD) questionnaires (Van der Grinten & Smitt, 1992)	3 ^a , 4, 6
Pittsburg Sleep Quality Index questionnaires (Buysse et al., 1989)	8
Karolinska Sleepiness Scale (KSS) (Åkerstedt & Gillberg, 1990; Kaida et al., 2006)	8
Samn-Perelli 7-point Fatigue Scale (SPFS) (Samn & Perelli, 1982)	8

^a Method used by primary cited studies.

^b Method used in secondary analysis of cited studies.

^c Method used, but results not published.

11.2.3. Recommendation on methods for (dis)comfort research

When studying (dis)comfort in seating and sleeping, it is recommended to always combine both objective and subjective study methods in order to research, improve and evaluate seat designs, as it is the human's opinion and physiology that in the end counts in product use. The human opinion is subjective, thus finding correlations between objective and subjective (physiological) measurements could help designers, engineers and scientists in their research and design process.

In sleep research, polysomnography (PSG) (Troester et al., 2023) is the golden standard to quantify sleep time, to differentiate sleep stages, and to assess sleep fragmentation (Grote & Zou, 2017), and is therefore recommended to use as a qualitative method. As this is an invasive method that can limit natural behaviour (due to leads and sensors connected to the body), combining it with purely questionnaire-based studies is advised. As PSG is also labour intensive, it is challenging to acquire large datasets in healthy subjects. Therefore, PSG is recommended for objective qualitative sleep research (in a controlled environment) in smaller studies, where questionnaires are recommended for large scale participatory studies (subjective quantitative research).

For seat research, it is advised to use observations of the user, posture analysis, pressure mapping, pressure discomfort threshold mapping (PDT), electromyography (EMG), and anthropometric measurements (Molenbroek, Albin, & Vink, 2017) (e.g. from databases, like DINED 1D (Molenbroek et al., 1984-2020), DINED mannequin (Huysmans, Goto, Molenbroek, & Goossens, 2020) and CAESAR (Robinette, Blackwell, Daanen, Boehmer, & Fleming, 2002)) next to (dis)comfort questionnaires, as these might give background information on the reasons of experiencing (dis)comfort.

11.3. Recommendations for further research based on this dissertation

From the study results in this dissertation, several questions arised for further research.

Part 1 shows that time affects experienced (dis)comfort and that discomfort decreases and comfort increases over the course of a sitting activity. It is however the question if the observed effects at the end of the sitting activity on (dis)comfort in Chapter 3 are due to the participants being conscious of time and the end of the sitting activity. Further research is therefore recommended (e.g. by means of a long-term comfort experiment where half of the participants are not conscious of the duration of the experiment nor the actual time). It would also be interesting to investigate to what extent time affecting experienced (dis)comfort correlates with the peak-end rule described by Kahneman, Fredrickson, Schreiber, and Redelmeier (1993) (which argues that the peak and end level of an experience are eventually remembered, where time is of less influence (Fredrickson & Kahneman, 1993)) in a seating context. E.g. would purposefully increasing comfort/decreasing discomfort of a seat at the end of transit positively affect the total seating/travel experience, and would it, especially in a commercial context (e.g. rail, bus

and aviation), positively affect the passenger's willingness to travel with the operator again. If the user is conscious of the remaining travel time, the peak-end rule might have an effect on (dis)comfort experience and/or affects the willingness to make use of a seating product again; then designers, engineers and scientists could make use of these effects in their seating, cabin and travel designs. Such application would require further research, i.e. with prototype seats for experimental (dis)comfort evaluation.

The studies in Part 2 show that a human contoured seat could be achieved with comparable (dis)comfort to a traditional seat, while being more compact and light weight. This was achieved by both the curvature and the material used. The study of Chapter 4 used a single curved backrest frame for the use in a full-flat business class seat, allowing it to be stretched into a full-flat bed (as demonstrated in Chapter 5, see Figure 5.6). However, a double curved backrest design could result in a stiff and strong backrest framework which at the same time could be light weight when using composite materials. The more compact design and curvature of the backrest could allow for more knee space for the occupant behind. This is especially interesting in automotive seating (Franz, Kamp, et al., 2011), public transport seats (e.g. trains) and Economy and Premium Economy Class seats in aviation. Such a double curved backrest is being developed by RECARO Aircraft Seating GmbH & Co. KG, which gives extra knee space at the sides of the seat backrest (see Figure 11.1). The (long-term) effects of such a double curved backrest on (dis)comfort should be investigated further, for both the seat occupant and the person sitting behind the human contoured seat.



Figure 11.1 | RECARO Aircraft Seating human contour-based prototype seat (left) as presented at the Aircraft Interior Expo 2019 in Hamburg, Germany. The double curved backrest provides additional (knee) space for the occupant behind the seat. Photo by Peter Vink.

Part 3 shows that people change posture and move their limbs during sleep, and that sleep space limitation has effect on sleep quality and comfort. The study results indicate that a space reduction can be achieved with acceptable/ comparable sleep quality and comfort ratings compared to a '*normal*' size bed.

As described in Chapter 7, some research has been conducted on sleeping postures (although collecting sleeping postures was seldom these studies' focus) and to some extent on movement. However, these studies are limited to body orientation and movement count. More detailed information on limb movement and orientation is missing, where this can be of interest in determining what should be facilitated in a limited sleep space design for full-flat sleeping. These postures and movements (also considering anthropometric diversity of the population) should be taken in consideration in sleep space envelope design. Therefore, specific research on a more detailed collection and analysis of sleep postures and movement during sleep is recommended. It is recommended to conduct such research in both a for the participant familiar sleep space at home (as they will show more natural behaviour opposed to a less familiar but more controlled lab environment, which one might want to facilitate in a less familiar context such as in transit), and in the application context (as environmental factors may have major influences on the participant's behaviour during sleep, e.g. vehicle movement, vibration, environmental noise, etc. (Matsangas & Shattuck, 2017)). The hypothesis that facilitating natural sleeping behaviour (e.g. facilitating postural change and movements) in transit could benefit sleep quality and comfort, should be investigated further. It is thus the question to what extent sleep space envelope reduction influences sleep postures and movement, and to what extent reduction in sleeping postures and (micro)movements influence sleep quality and comfort. Thus, further research is recommended on the effect of facilitating and limiting sleeping postures on sleep quality and comfort.

Chapter 8 describes how reducing the sleep space envelope affects sleep quality and comfort. This study was limited in sample size and diversity (predominantly young adults), but also in duration (only one night in each condition). Expanding the sample with a larger and more diverse (in both age and ethnicity) population sample is recommended to make the results more representable. Also, consecutive nights in limited sleeping space envelope conditions are of interest, especially in professional sleeping/berthing contexts (e.g. flight attendants and pilots in crew rests, and sailors in navel berthing compartments), as acclimatisation/ familiarisation may impact both occupants' sleep behaviour (e.g. adjusting movements to limitations) and the sleep quality and comfort experience. It is also recommended to investigate the effects of sleep space reduction in 3D (i.e. including height) and of more diverse shapes (not limited to a rectangle, but more diverse shapes that can be compacted). Although it was the original intent of this study to also investigate 2D shape variation, it was limited to 2D rectangle due to limited resources and time. Future research should explore potential shapes that can be stacked close to each other while providing sufficient room for natural sleep behaviour (i.e. movement and postures). It is important to consider anthropometric variation (e.g. limb length/stature, waist circumference) within the target population, as these influence sleep space design. Here, frequently observed postures and movement (from previously recommended

future research) could give direction to the design. Further research is needed regarding in what way (shape, height) a 3D limited sleep space design affects sleep quality and comfort (see §11.4.2.2). Studying sleep quality by means of PSG and performed postures /movement is highly recommended (as discussed in §11.2.3), as this gives insight on sleep phase effects (especially relevant, due to the importance of the amount of S3 and REM sleep).

Part 4 shows that head support when watching IFE could benefit the comfort experience, and that pressure sensitivity is different for different areas of the head and neck. These insights could be used in headrest design, e.g. in providing a forward tilting headrest and choices in headrest cushioning firmness. It is recommended to test a design based on this background knowledge.

Chapter 9 shows that head support when watching IFE in a slouched posture had no significant short-term effects on measured muscle activity. However, there might be long-term effects. The head-neck muscles need to keep the head upright by means of continuous (micro)contraction(s). Since passengers may watch IFE for a prolonged period (e.g. watching two movies on a long-haul flight), it is recommended to study the long-term effects of this slouched posture, with and without head support, on experienced (dis)comfort against muscle activity and fatigue over time. Although this study's result indicates muscle contraction is minimal (as low EMG activity and no significant differences have been found between conditions with and without headrest), prolonged static muscle contractions of > 5%MVC can cause fatigue (Jonsson, 1978; Jørgensen, Fallentin, Krogh-Lund, & Jensen, 1988; Sjøgaard, Kiens, Jørgensen, & Saltin, 1986) where micromovements can promote blood circulation. As the *m. trapezius pars descendens* showed >5%MVC, fatiguing could be expected. It is the question if local postural muscle fatigue and/or micromovements that might relieve fatigue will occur in the context of watching IFE. Therefore, further research on the long-term effects of head support versus no head support would be valuable. The use of fine-wire- or needle-electrodes in order to include the *m. splenius capitis* and the *semispinalis* muscles can be considered in future studies, although this might be quite invasive. As participants indicate they expect to experience more comfort with head support, it would be interesting to investigate to what extent such expectations influence the all over experienced (dis)comfort (e.g. demonstrated by Naddeo, Cappetti, Califano, and Vallone (2015) in bed mattresses), in line with the effect of *expectations* in comfort models of De Looze, Kuijt-Evers, and Van Dieën (2003), Vink and Hallbeck (2012), and Naddeo, Cappetti, Vallone, and Califano (2014).

Chapter 10 gives a dense pressure sensitivity map of the head and neck, which can be used in e.g. headrest padding design. Franz et al. (2012) investigated comfortable foam firmness for three large regions (back of the head, neck and shoulders) for headrest design. The head sensitivity map in this dissertation presents a more detailed PDT map that can result in more finetuned headrest foam designs. Although the sensitivity map is highly detailed, it is limited in the sample size compared to e.g. Shah and Luximon (2021) (n=218, all Chinese). The head sensitivity map could be improved by further research using the described method in a larger and more diverse (in both age and ethnicity)

population sample. Although the point density of this study is the highest to date of publication, an even higher point density may be needed for certain applications, such as around the ear, nose, eyes and mouth for products like headphones, glasses and facial masks which need to be worn for an extended time. Maybe even in-ear studies can be considered for earbuds and plugs. However, for the application of a seat headrest, the point density could be considered as sufficient (also, because contact points might differ between occupants). This study focussed on short-term PDT, whereas for most products long-term effects of pressure are of interest. Such an attempt has been made in an unpublished study by van Dijk, Keesmaat, Ligtenberg, Smulders, and Huysmans (2021) for specifically a head mounted camera for surgeons. Ten participants wore two head mounts – one that pressed on the most sensitive-, another that pressed on the least-sensitive-areas according to the map presented in Chapter 10 – for 3.5h each, and evaluated the overall comfort and discomfort each 15 minutes and local perceived discomfort (LPD) each 30 minutes. Pressing on sensitive areas scored significantly worse on comfort and discomfort. Comfort decreased and discomfort increased also faster when pressing on sensitive areas opposed to pressing on least sensitive areas. These results indicate that the *'head, face and neck pressure sensitivity map'* presented in Chapter 10 could also be used when designing for long-term comfort. Further research on long-term pressure sensitivity (causing discomfort or maybe even pain) is highly recommended. It is also recommended to further investigate to what extent the PDT map is useful in seating (and other product) design. This could be done by designing and testing prototype headrests for e.g. supporting the head for watching IFE and reclined sleeping (see also §11.4.2.4), to evaluate (dis)comfort experience and sleep quality, and possible improvements on the PDT map (e.g. by means of increasing the sample and/or point density in relevant areas).

11.4. Recommendations for future research beyond this dissertation

Some topics were not extensively studied in this dissertation, but may be relevant to the context of designing comfortable seating environments in vehicles. Therefore, some suggestions and recommendations for future research (and design) are formulated below. As during the writing of this dissertation, these subjects were touched upon, observed and/or identified in research projects, communications with users and professionals, conferences, and/or found in literature.

11.4.1. Seating research recommendations

As discussed in this doctoral dissertation, it is important in seat design to consider seat contour, design for a broad population (ideally for all (Molenbroek, Groothuizen, & de Bruin, 2011)), softness (pressure distribution and sensitivity), and in seat activities and their related variations in postures. Also cabin influences, like temperature, humidity, noise, smell, and vibration (Bouwens, 2018) should be considered. Passengers and crew are also limited in choosing their preference in transit. Giving more forms of control can

benefit comfort (Lee & Brand, 2005; Vink & Brauer, 2011). Based on insights gained during this PhD (not the core of this dissertation, but potentially relevant for science and industry), some suggestions for further research on seating in transit are:

11.4.1.1. Ideal pressure distribution

The ideal pressure distribution for sedan cars (driver seat) has been explored rather well (e.g. Mergl (2006) and Zenk (2008)). It is the question whether this ideal pressure distribution is applicable to other vehicle seats and in-seat activities. Therefore, for other vehicles the pressure distribution in relation to conducted activities needs to be studied further.

11.4.1.2. Personal temperature control for seating

The temperature in an airplane cabin can vary significantly (Cui, Ouyang, & Zhu, 2014; Müller et al., 2022; Pang, Qin, Liu, & Liu, 2014), causing passengers to complain about too hot or cold cabins (Cui et al., 2014; Nicholls, 2023). Also, new electric vehicles need to be more efficient with vehicle interior climate control to increase range and/or lower emissions. As upcoming automated vehicles increase freedom of in-vehicle activity, the need for thermal management in electric vehicles is expected to increase (Kwon, Kim, Lee, Lee, & Ju, 2023). As temperature preferences differ between individuals (Roelofsen, 2016), in seat active cooling and heating (e.g. Y. F. Zhang, Wyon, Fang, and Melikov (2007), Melikov, Ivanova, and Stefanova (2012), Fan and Zhou (2019) and Matsumoto, Kanamaru, Tan, and Kamioka (2023)) with personal control could be beneficial to vehicle seat comfort design (Cui, Wu, Ouyang, & Zhu, 2017; Luo et al., 2014; Smulders, 2018; Vink & Brauer, 2011). Further research is recommended also in this area (Hedge, Khalifa, & Zhang, 2009).

11.4.1.3. Seat controls

Seat designs sometimes provide adjustment controls to support a broader population and a variety of in-seat activities and postures (e.g. Figure 5.4). As seat controls can vastly differ, passengers may find it difficult to adjust their seats (Groenesteijn, Vink, Looze, & Krause, 2009; Vink & Brauer, 2011). As shown in office seats, 63% of the users do not adjust their seat (Vink, Porcar-Seder, de Pozo, & Krause, 2007). Recommendations on pre-set seat angles based on activity and standardisation in seat control *use cues* (Schifferstein & Hekkert, 2011) could benefit user understanding and use of seat adjustment features (including automated adjustment features based on e.g. pressure distribution (Franz, Zenk, Vink, & Hallbeck, 2011; Vink & Brauer, 2011; Zenk, Franz, Bubb, & Vink, 2012)), which will benefit user (dis)comfort. Further research on this area is recommended as well.

11.4.2. Sleep research recommendations

Sleep ergonomics in general needs more attention, let alone sleeping in transit. As humans we spend approximately one third of our life sleeping. Nevertheless, the field of sleep study is relatively young with still a lot of unknowns, such as the reason why we sleep and dream. For example scientists did not discover REM sleep – a fundamental step in the sleep cycle – until 1953 (Aserinsky & Kleitman, 1953), simply because technology was not ready to measure brainwaves accurately enough. Research on sleep medicine is extensive, however published research on bed ergonomics and its effects on sleep quality and comfort is surprisingly limited.

In transit, sleeping is one of the most performed, requested and/or rated as most important activities in transit (Bouwens, Tsay, & Vink, 2017; Gregghi, Rossi, Souza, & Menegon, 2012; Kim, Jeon, Kim, Yeo, & Kim, 2022; Liu, Yu, & Chu, 2019; Smulders, 2018). This is not only limited to leisure travel, but also concerns a vast working population, often working in safety critical environments (Jay, Aisbett, Sprajcer, & Ferguson, 2015). Sleeping in transit also has a lot of additional challenges with environmental control (Bouwens, Hiemstra-van Mastrigt, & Vink, 2018a; Caddick, Gregory, Arsintescu, & Flynn-Evans, 2018) – like (sudden) noise (Hansen & Holmen, 2011; Sunde, Bråttveit, Pallesen, & Moen, 2016), vibrations (Arnberg, Bennerhult, & Eberhardt, 1990), movement (Stevens & Parsons, 2002), light, temperature (Matsangas & Shattuck, 2017, 2021; Matsangas, Shattuck, & McCauley, 2015; Rosekind, Gregory, Co, Miller, & Dinges, 2000), privacy (Harrison, Sommer, Struthers, & Hoyt, 1986; He & Vink, 2020), and bodily support (Caballero-Bruno, Wohllebe, Töpfer, & Hernández-Castellano, 2022; Gregghi et al., 2012; Smulders, 2018; Stanglmeier et al., 2020) as opposed to normal sleep in a bed at home. Providing more control over the sleeping environment (Jay et al., 2015) and personalisation of bedding systems (Smulders, 2018; van Deun et al., 2012; Verhaert et al., 2011) in vehicles might be a key element to improve sleeping comfort in transit.

Based on insights gained during this PhD (not the core of this dissertation, but potentially relevant for science and industry), some suggestions for further research on sleeping in transit are:

11.4.2.1. Movement and motion sickness effects on sleep

Vehicle movement poses a (possible) challenge to sleeping in transit, as movement can disturb sleep and can cause motion sickness (Matsangas et al., 2015) due to the mismatch between visual, vestibular and somatosensory motion cues (Smyth, Robinson, Burridge, Jennings, & Woodman, 2021). This is especially relevant in an automotive (e.g. due to tight turns, breaking and accelerating in traffic) (Diels & Bos, 2016; Smyth, Jennings, & Birrell, 2020) and nautical context (e.g. due to weather, waves and tidal influences) (Guignard & McCauley, 1990; Matsangas et al., 2015; Stevens & Parsons, 2002), and to a lesser extent in civil aviation (e.g. turbulence) (Rosekind et al., 2000) and rail (e.g. vibrations, track changes, taking (banking) corners, tilting carriages, breaking and accelerating) (Guignard & McCauley, 1990; Suzuki, Shiroto, & Tezuka, 2005). Further research is needed on the effects of vehicle movement and motion sickness on in-vehicle sleeping and their specific contexts, and how to mitigate them through design.

11.4.2.2. Minimal 3D sleep space envelope

A recommendation on a minimal 3D space envelope needed for qualitative sleep would be useful for designers and engineers to balance sleep quality and comfort against the limited space volume available in vehicles for economical and sustainability reasons. Although an attempt has been made in this dissertation to define a minimal space envelope with acceptable sleep quality and comfort (see Chapter 8), relations with anthropometrics, shape and height are missing. Further research is needed on the effects of 3D space volume (thus also height) on sleep behaviour, sleep quality and comfort by means of video observations, PSG, questionnaires and possibly interviews. It could be insightful to compare behaviour (movement), sleep quality and comfort between a normal bed or current in-vehicle seats/berths/beds and a minimal space envelope. Special attention should be given to space allowing or limiting natural limb movement and postural shifts and their (long-term) effects on sleep quality and comfort. E.g. limiting feet rotation (to change from one posture to another) could have a negative effect on all-over sleep efficiency and comfort, but this needs to be investigated.

11.4.2.3. Minimal backrest recline for sleep

A minimal backrest recline for acceptable/adequate sleeping can be used as a guideline in seat design that facilitates sleep in space volume limited environments. Sleeping in a reclined position (relatively upright) is challenging (Gregghi et al., 2012). Aeschbach, Cajochen, Tobler, Dijk, and Borbély (1994), Nicholson and Stone (1987), Hayashi and Abe (2008), and Roach, Matthews, Naweed, Kontou, and Sargent (2018) show a clear relation between backrest angle and sleep efficiency (see Figure 11.2). The flatter the better (Smulders, 2018), but as this is not possible in every context, insight on a minimal backrest recline recommendation for sleep would be useful.

Stanglmeier et al. (2020) give a biomechanical based recommendation of 155° backrest recline with a 40° seat pan angle. Caballero-Bruno et al. (2022) showed that in a moving vehicle a 177° backrest recline is more comfortable and is more effective for sleep than a more upright backrest recline of 150°. Vledder et al. (2024) recommend a back rest angle of at least 130°. However, sleep quality was not measured by means of PSG, and postural change and limb movement were not investigated. Further research is needed on reclined sleep with the aim to come up with seat recline recommendations.

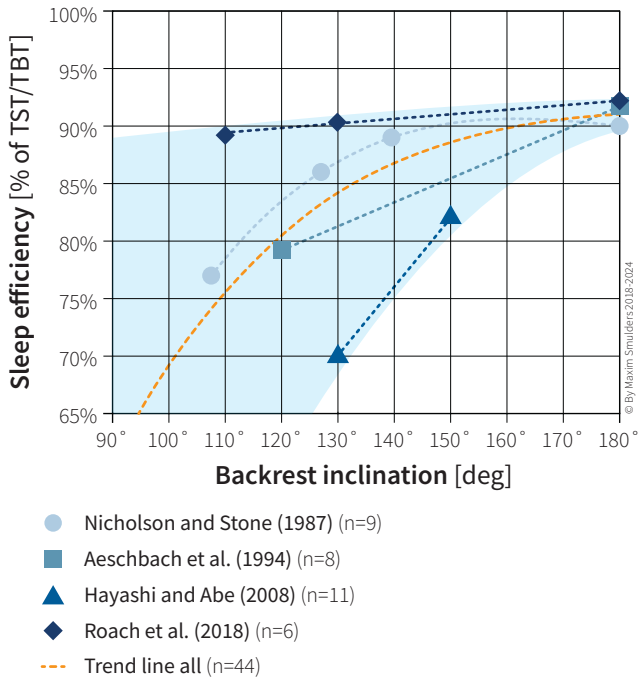


Figure 11.2 | Sleep Efficiency (SE) [percentage of Total Sleep Time (TST) over Total Bed Time (TBT)] against backrest recline [degrees]. An SE of $\geq 85\%$ is recommended (Ohayon et al., 2017). Figure by Maxim Smulders (2018-2022).

11.4.2.4. Head support for reclined sleeping

Possible improvement of reclined sleeping could be found in supporting the head. Smulders (2018) hypothesises that the head ‘falls’ (see Figure 11.3) due to muscle relaxation in N3 (deep sleep), triggering the vestibular system and thereby causing the brain to ‘wake up’ (as the core brain assesses stimuli relevant for self-preservation), resulting in bouncing between N1 and N2 (light) sleep, but limited up to no N3 (deep) and REM (dream) sleep. Head support for limited backrest recline conditions could possibly improve sleep comfort and sleep efficiency (Bouwens, Schultheis, Hiemstra-van Mastrigt, & Vink, 2018b; Smulders, 2018). Further research is recommended to investigate the *falling head motion reflex* hypothesis and the possibility to mitigate this by means of a headrest design.

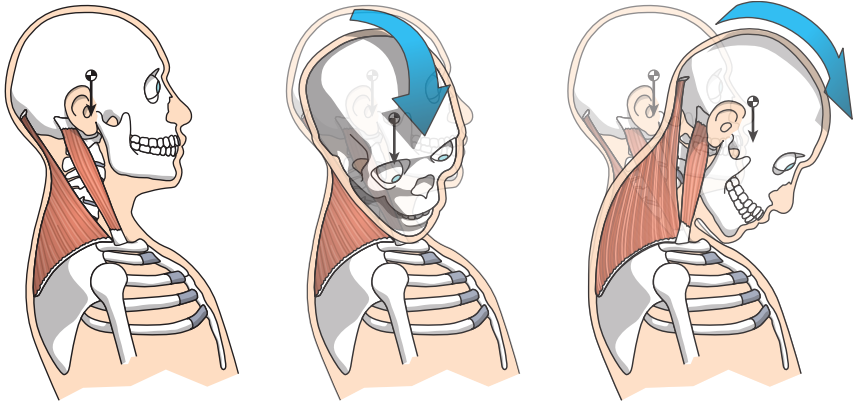


Figure 11.3 | When the muscles relax in sleep, the head falls sideways or forward as the head's gravitational point lies in front of the rotational point in the spine without sufficient recline and/or head support. Illustration by Maxim Smulders, 2018.

11.4.2.5. Safety of in-transit sleeping

As vehicles move, accelerate and (rapidly) decelerate, restraining systems are needed for occupant safety. The challenge here is to safely restrain and support the occupant while allowing for natural movement during sleep and minimise impact on sleep quality and comfort. In reclined seating, occupants have a greater chance to slide underneath the seatbelt in a crash event (*'submarining'*) (Tang & Liu, 2012; Tang, Zheng, & Zhou, 2020). A reclined seat position in a car is associated with increased occupant mortality in motor vehicle collisions (Dissanaike, Kaufman, Mack, Mock, & Bulger, 2008). Stanglmeier et al. (2020) therefore point out that a full-flat seat might not be possible in a moving car, but their biomechanically preferred seating position for sleeping with tilted seat pan angle might be sufficient for occupant safety. Results of Wiechel and Bolte (2006) suggest that a tilted seat (not a recumbent position) can prevent *submarining* and results in less injuries. But also knee bolsters and airbags, seat pan deformation reduction, seat belt locking and new restraint systems should be considered (Ji, Huang, & Zhou, 2017; Tang et al., 2020; Wiechel & Bolte, 2006). Also, restraining adjustment should be considered for reclined and full-flat sleeping.

Another safety challenge besides restraining is the take-over request (TOR) in automated vehicles (AV's) to drivers who are sleeping (Vogelpohl, Kühn, Hummel, & Vollrath, 2019). No (adequate) awakening can result in accidents. Especially waking drivers from deep sleep can be difficult, and when woken these drivers will feel disorientated for a prolonged time (Åkerstedt et al., 2002; Dinges, Orne, & Orne, 1985) (although this consensus has been challenged by recent literature (Hilditch & McHill, 2019)).

Thus, further research is needed on restraining and safety systems (Caballero-Bruno et al., 2022), seat configurations for sleeping in moving vehicles (not only limited to cars) with minimal impact on sleep quality and comfort, and AV take over requests after sleeping.

11.4.2.6. Personalised mattress support (smart bed)

For a comfortable and qualitative good sleep, adequate musculoskeletal support is needed (Coenen, 2011; Haex, 2004; Verhaert et al., 2011). Where a bed at home can be tailored to the individual user, in-vehicle occupants (in general) frequently alternate. These occupants differ in anthropometrics (Molenbroek et al., 2017) and in personal and cultural preferences (Haex, 2004; Vink et al., 2021). The development of personalised bedding systems in vehicles with frequently changing occupants should therefore be considered.

Differences in anthropometrics and body build require different pressure distributions. E.g. hip and shoulder distance are different for tall and small people, and heavier people need firmer support than lighter people (Haex, 2004). Thus, some form of local measuring and control of bedding firmness to adjust for body shape, weight (distribution) and posture by means of sensors and actuators (e.g. pneumatic actuators (Franz, Zenk, et al., 2011), soft-robotics bellows (Buso et al., 2020; Roozendaal et al., 2022), and/or actuated slatted base (Verhaert et al., 2011)) could make for adaptable beds.

Further research on personalised seating and bedding design for sleeping in vehicles is recommended.

11.4.2.7. Personal temperature control for sleeping

Local and individual temperature control can help with sleeping (Rosekind et al., 2000), as ideally the cabin and head are relative cool (Coenen, 2011; Kawabata & Tokura, 1996; Law, 2013), with a comfortable micro-climate temperature (temperature underneath the blanket) (Coenen, 2011; Haex, 2004; Lin & Deng, 2008). Local climate control is common in modern cars (i.e. with climate control, air conditioning, adjustable air vents and seat heating/ cooling), some sleeper trains provide private cabin temperature adjustments and many aircraft seats and some train seats have a passenger service unit (PSU) which provides some (but limited) climate control by means of an adjustable air vent. However, local and individual temperature control is limited in aviation, rail and naval contexts, where there are challenges with climate control in cabin and berthing spaces (Matsangas & Shattuck, 2017; Rosekind et al., 2000). As temperature preferences are very individual (Roelofsen, 2016), some form of personalised micro-climate control (Caddick et al., 2018; Smulders, 2018; Xin, Cui, & Zeng, 2019) would be interesting to explore.

Further research on personalised temperature control for sleeping (and also seating) in vehicles is recommended.

11.5. Recommendations for industry based on this dissertation

The insights from answering the research questions in this dissertation (§11.1) can be used in (but are not limited to) seat design. Figure 11.4 gives an overview of how the background information gathered in the dissertation chapters can be used in the design of an aircraft business class seat. Depending on the context, requirements and limitations, these insights can also be applied in other seats and contexts. E.g. the head sensitivity model can also be used in designing head support for reclined sleeping (see also §11.4.2.4). Based on the studies in this doctoral dissertation, the following recommendations for industry can be given:

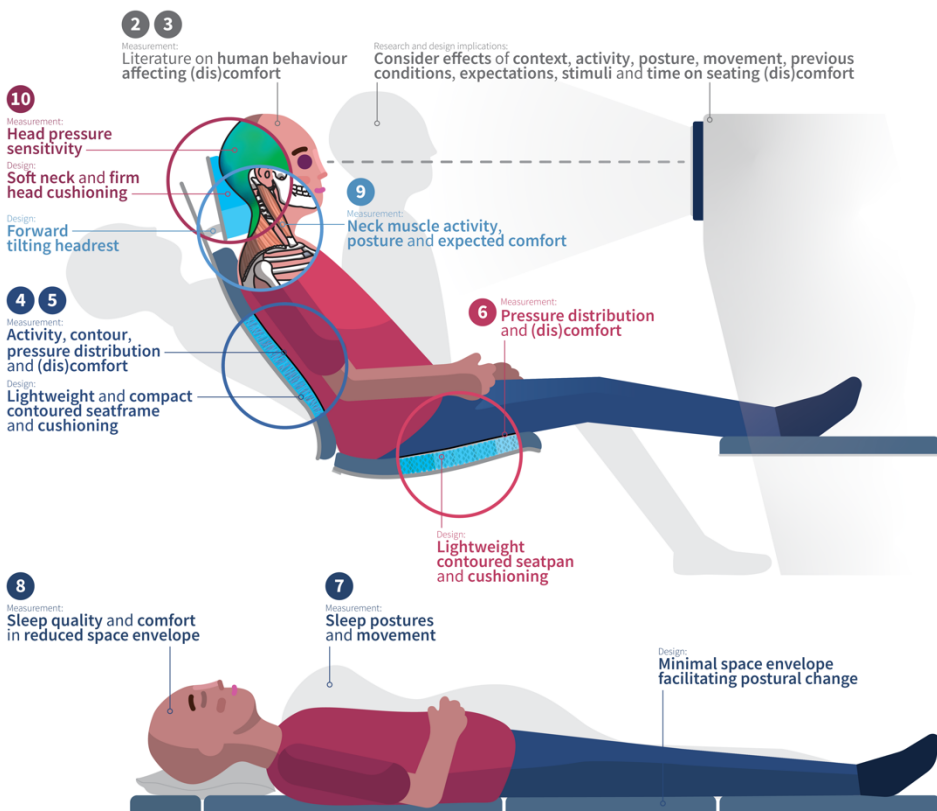


Figure 11.4 | Overview of dissertation chapters in relation to a full-flat business class seat.

11.5.1. Designing light weight seats based on the human contour

Designing vehicle seats based on the human contour can result in similar or more comfortable designs while reducing weight.

A human contoured seat could result in slimmer and curved backrests, allowing for more knee- and leg-space, while keeping (dis)comfort at comparable or better ratings to traditional seats. The use of a double curved construction and slimmer contoured cushioning could result in weight reduction. 3D scanning can be used to capture the human contour under seated load (Chapter 4 and 5). It is advisable to scan both the full participant in a vacuum mattress and the mattress imprint itself, as it provides additional information such as upper-leg thickness for e.g. folding-table height design (Chapter 4 and 5).

However, the challenge for a globally used seat is to accommodate a vastly diverse international population (anthropometrically and culturally) and a multitude of postures (Chapter 4 and 5). This requires conscious decision-making by designers and engineers in finding overlap between populations/activities (to facilitate a large population and posture variety) and dealing with trade-offs (excluding a part of the population and/or activities) (Chapter 5). For this purpose, the use of a superimposing method (Chapter 5, Franz, Kamp, et al. (2011); Hiemstra-van Mastrigt (2015)) for 3D scans is recommended. Using average human curvatures is not recommended (Chapter 4 and 5). The use of additional biomechanical models (especially on shear force (e.g. Goossens and Snijders (1995))) is recommended as well. Contoured seats with bolsters on the sides are advised as these lead to larger contact areas, and more comfort in the seat (Wegner, 2020). Additional weight reduction can be achieved in foam reduction (e.g. by means of knitted structures (Chapter 4) or foam spring structures (Chapter 5), with the additional benefit of better moisture control compared to closed cell foams (Bartels, 2003; Mazari, Chotebor, Naeem, Mazari, & Havelka, 2016; Nemcokova, Glombikova, & Komarkova, 2023)) while keeping a good pressure distribution (to be evaluated with pressure mapping and (dis)comfort studies (Mergl, 2006; Zenk, 2008)), and by means of topology optimised seat shell/structures (Chapter 6). It is important to keep in mind cultural influences on seat aesthetics and cushioning softness (Vink et al., 2021).

It is always recommended to validate the seat design with (dis)comfort user tests (Chapter 4-6, 8 & 9).

11.5.2. Design for human activity

Design vehicle seats that facilitate preferred and dominant activities and their related (varied) postures.

In vehicle interior design it is important to start with investigating human behaviour and the activities humans perform in transit (Chapter 2, 4-6, 7, 8 and 9). These activities determine what postures people take and thus need to be facilitated within the cabin, and predominantly by the seat (Chapter 4, 5, 7, 8 and 9). Additionally, facilitation of variation of posture is important to prevent discomfort, pain and ulcers, and therefore the interior and seat should facilitate posture variation, both in seating (Chapter 4, 5 and

9) and sleeping activities (Chapter 7 & 8). When postures and postural variation are known, the necessary bodily support and required space envelope both need to be determined. It is up to the designers/engineers to balance space and weight needs for comfort against economic factors. It is important that material and design choices do not obstruct the users in their micro (limb, weight redistribution) and macro (postural) movements (Haex, 2004; Smulders, 2018). E.g. too soft cushioning and too thick memory foams can obstruct movements and postural changes.

11.5.3. Design for comfort over time

When designing transportation services, cabins and seats, keep in mind that there is an effect of time duration and time awareness on travel- and seating (dis)comfort.

In general, over time discomfort will increase and comfort will decrease (Chapter 2 and 3). Time awareness can result in tapering of (dis)comfort, or even increase comfort and decrease discomfort close to the end of transit (Chapter 3).

Managing the travel experience over time could benefit (dis)comfort experience (Bouwens et al., 2017). A condition could be added to initiate postural shifts or distractions, such as a meal service (Bouwens et al., 2017), a game (Bouwens, Fasulo, et al., 2018c) and IFE/virtual environment (Lewis et al., 2016), that has a positive effect on the (dis)comfort experience.

11.5.4. Design for IVE/IFE

Design seats for comfortably watching in-vehicle entertainment (IVE/IFE) that can recline backwards (120-130°) and provide adjustable forward tilting head/neck support. A headrest should be soft at the neck area and can be firmer at the back of the head to support the head.

As in-vehicle entertainment (IVE/IFE) is one of the most performed in-seat activities in transit, facilitating this activity can improve passenger comfort. Ideally the user can adjust the backrest angle (120-130°), and the headrest height and angle themselves for when watching IVE/IFE (Chapter 9). Make sure the headrest does not protrude at the shoulder region (thus sufficient height adjustment to facilitate a large population) and does not push the head and neck more forward than the backrest recline, as it otherwise may push the head, neck and/or shoulders forward, possibly resulting in muscle strain. When the head is supported with a headrest, the area interfacing with the neck should be soft and with the back of the head more firm (Chapter 10, Franz et al. (2012)). It is recommended to use the detailed pressure sensitivity model of the head, face and neck from Chapter 10 as a reference in designing comfortable headrests for watching IFE/IVE and reclined sleeping in vehicles.

11.5.5. Design for sleeping in transit

Design compact sleep spaces with a minimal (or considered acceptable) deteriorating effect on sleep quality and comfort. This can be achieved by reclined sleeping in a seat or full-flat sleeping in a minimal space. Providing sufficient space and bodily support for postural change, predominantly between lateral and supine transitions, limb movement and anthropometric variation is recommended. When supporting the head, the headrest's interfacing cushioning should be soft in areas around the ears, face and neck, where they can be firmer at the back of the head and jaw line to provide support.

Although full-flat sleeping can be costly by means of required space volume and associated costs, some passengers are willing to pay for its productivity benefits (Hugon-Duprat & O'Connell, 2015; Kuo & Jou, 2017; Smulders, 2018) or it is essential to operational safety as sleep impacts staff alertness, effectiveness, and comfort (as discussed in Chapter 1). Reclined sleeping can be more space efficient and/or necessary for collision safety in moving vehicles (Caballero-Bruno et al., 2022; Stanglmeier et al., 2020).

For both reclined and full-flat sleeping, ideally the sleep space allows for postural change, as people make micro and macro movements during sleep to relieve soft tissue. At least facilitate lateral and supine postures, as these are most common (Chapter 7). Important here is that people should not be obstructed in rotating the body to change between lateral and supine. This means that the seat/bed cushioning softness should not limit movement and postural change (Haex, 2004), nor should the space volume restrict (e.g. too narrow space for the feet restricting their rotation and thereby limiting postural change). Especially in seating this can be challenging, as cushioning firmness needs to be different for seating and sleeping conditions (Smulders, 2018). An option here could be a soft area in the middle of the seat at shoulder height and firm lumbar support, or a middle section of the backrest cushioning that can slide downwards, allowing the shoulder to sink in and provide lower-back support in a lateral position in the seat (§5.3.2).

In full-flat sleep the necessary space volume can be reduced (~25% of a normal one-person bed of 190 x 90 cm) with minimal effect on sleep quality and comfort (Chapter 8). However, further research is needed on the impact of shape of the sleeping space and anthropometrics. Non-rectangular shapes should be explored, as they can provide new ways of compact stacking or space for other apparatus (e.g. storage, electronics, mechanisms, safety equipment, climate control, etc.).

In reclined sleep, supporting the head could benefit sleep quality and comfort (Bouwens, et al., 2018b; Smulders, 2018; H. Zhang, Meng, Gong, & Wang, 2021). When the head is supported with a headrest, the area interfacing with the neck, ears and face should be soft, where the back of the head and jawline can be firmer to support the majority of the weight of the head (Chapter 10).

11.6. Final statement: to conclude this doctoral dissertation

This doctoral dissertation provided new ideas and solutions for seat, bed and headrest design, and provides new methods and considerations to research comfort.

As shown in this doctoral dissertation, seat design should be activity based, to accommodate human behaviour, posture variation and in-seat movement, as these impact user (dis)comfort. Human contoured seating can improve seating comfort and reduce weight. Sleep space envelope reduction negatively influences sleep quality and comfort, but an acceptable balance can be made between sleep quality and comfort against vehicle space volume used. Head support for watching IFE can improve user comfort.

Although sleep ergonomics has some attention in science, it is surprising how limited the scientific field on sleep ergonomics is developed. Although a first exploration on this topic has been done in this doctoral dissertation, more attention should be given to sleep ergonomics as this is relevant to both bed design and to vehicle seat design.

11.7. References

- Aeschbach, D., Cajochen, C., Tobler, I., Dijk, D.-J., & Borbély, A.A. (1994). Sleep in a sitting position: effect of triazolam on sleep stages and EEG power spectra. *Psychopharmacology*, 114(2), 209-214.
- Åkerstedt, T., Billiard, M., Bonnet, M., Ficca, G., Garma, L., Mariotti, M., . . . Schulz, H. (2002). Awakening from sleep. *Sleep Medicine Reviews*, 6(4), 267-286. doi:10.1053/smr.2001.0202
- Åkerstedt, T., & Gillberg, M. (1990). Subjective and objective sleepiness in the active individual. *International Journal of Neuroscience*, 52(1-2), 29-37. doi:10.3109/00207459008994241
- Anjani, S., Kühne, M., Naddeo, A., Frohriep, S., Mansfield, N., Song, Y., & Vink, P. (2021). PCQ: Preferred Comfort Questionnaires for product design. *WORK*, 68(s1), S19-S28. doi:10.3233/WOR-208002
- Arnberg, P.W., Bennerhult, O., & Eberhardt, J.L. (1990). Sleep disturbances caused by vibrations from heavy road traffic. *The Journal of the Acoustical Society of America*, 88(3), 1486-1493. doi:10.1121/1.400305
- Aserinsky, E., & Kleitman, N. (1953). Regularly occurring periods of eye motility, and concomitant phenomena, during sleep. *Science*, 118(3062), 273-274. doi:10.1126/science.118.3062.273
- Bartels, V.T. (2003). Thermal comfort of aeroplane seats: influence of different seat materials and the use of laboratory test methods. *Applied ergonomics*, 34(4), 393-399. doi:10.1016/S0003-6870(03)00058-9
- Bouwens, J.M.A. (2018). *Design considerations for airplane passenger comfort*. (Doctoral Dissertation), Delft University of Technology, Delft, The Netherlands. doi:doi.org/10.4233/uuid:306dd9f8-fab9-4f1f-8c1a-1a208e815c21
- Bouwens, J.M.A., Fasulo, L., Hiemstra-van Mastrigt, S., Schultheis, U.W., Naddeo, A., & Vink, P. (2018c). Effect of in-seat exercising on comfort perception of airplane passengers. *Applied ergonomics*, 73, 7-12. doi:10.1016/j.apergo.2018.05.011
- Bouwens, J.M.A., Hiemstra-van Mastrigt, S., & Vink, P. (2018a). Ranking of human senses in relation to different in-flight activities contributing to the comfort experience of airplane passengers. *International Journal of Aviation, Aeronautics, and Aerospace*, 5(2), 9. doi:10.15394/ijaaa.2018.1228
- Bouwens, J.M.A., Schultheis, U.W., Hiemstra-van Mastrigt, S., & Vink, P. (2018b). Expected versus experienced neck comfort. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 28(1), 29-37. doi:10.1002/hfm.20721
- Bouwens, J.M.A., Tsay, W.-J.J., & Vink, P. (2017). The high and low comfort peaks in passengers' flight. *WORK*, 58(4), 579-584. doi:10.3233/WOR-172637
- Buso, A., Scharff, R.B., Doubrovski, E.L., Wu, J., Wang, C.C., & Vink, P. (2020). Soft robotic module for sensing and controlling contact force. Paper presented at the 2020 3rd IEEE International Conference on Soft Robotics (RoboSoft). doi:10.1109/RoboSoft48309.2020.9115970
- Buyssse, D.J., Reynolds III, C.F., Monk, T.H., Berman, S.R., & Kupfer, D.J. (1989). The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. *Psychiatry research*, 28(2), 193-213. doi:10.1016/0165-1781(89)90047-4

- Caballero-Bruno, I., Wohllebe, T., Töpfer, D., & Hernández-Castellano, P.M. (2022). The effect of seating recline on sleep quality, comfort and pressure distribution in moving autonomous vehicles. *Applied ergonomics*, 105, 103844. doi:10.1016/j.apergo.2022.103844
- Caddick, Z.A., Gregory, K., Arsintescu, L., & Flynn-Evans, E.E. (2018). A review of the environmental parameters necessary for an optimal sleep environment. *Building and Environment*, 132, 11-20. doi:10.1016/j.buildenv.2018.01.020
- Coenen, A. (2011). Sleep, the bedroom and the bed. *NSWO*, 22, 26-32.
- Cui, W., Ouyang, Q., & Zhu, Y. (2014). Field study of thermal environment spatial distribution and passenger local thermal comfort in aircraft cabin. 80, 213-220. doi:10.1016/j.buildenv.2014.06.004
- Cui, W., Wu, T., Ouyang, Q., & Zhu, Y. (2017). Passenger thermal comfort and behavior: a field investigation in commercial aircraft cabins. *International Journal of Indoor Environment and Health*, 27(1), 94-103. doi:10.1111/ina.12294
- De Looze, M.P., Kuijt-Evers, L.F.M., & Van Dieën, J.H.L. (2003). Sitting comfort and discomfort and the relationships with objective measures. *Ergonomics*, 46(10), 985-997.
- Diels, C., & Bos, J.E. (2016). Self-driving carsickness. *Applied ergonomics*, 53, 374-382. doi:10.1016/j.apergo.2015.09.009
- Dinges, D.F., Orne, M.T., & Orne, E.C. (1985). Assessing performance upon abrupt awakening from naps during quasi-continuous operations. *Behavior Research Methods, Instruments, & Computers*, 17(1), 37-45. doi:10.3758/BF03200895
- Dissanaike, S., Kaufman, R., Mack, C.D., Mock, C., & Bulger, E. (2008). The effect of reclined seats on mortality in motor vehicle collisions. *Journal of Trauma and Acute Care Surgery*, 64(3), 614-619. doi:10.1097/TA.0b013e318164d071
- Fan, J., & Zhou, Q. (2019). A Review about Thermal Comfort in Aircraft. *Journal of Thermal Science*, 28(2), 169-183. doi:10.1007/s11630-018-1073-5
- Franz, M., Durt, A., Zenk, R., & Desmet, P.M.A. (2012). Comfort effects of a new car headrest with neck support. *Applied ergonomics*, 43(2), 336-343. doi:10.1016/j.apergo.2011.06.009
- Franz, M., Kamp, I., Durt, A., Kilincsoy, Ü., Bubb, H., & Vink, P. (2011). A light weight car seat shaped by human body contour. *International Journal of Human Factors Modelling and Simulation*, 2(4), 314-326. doi:10.1504/IJHFMS.2011.045002
- Franz, M., Zenk, R., Vink, P., & Hallbeck, S. (2011). The effect of a lightweight massage system in a car seat on comfort and electromyogram. *Journal of manipulative and physiological therapeutics*, 34(2), 107-113. doi:10.1016/j.jmpt.2010.12.002
- Fredrickson, B.L., & Kahneman, D. (1993). Duration neglect in retrospective evaluations of affective episodes. *Journal of personality and social psychology*, 65(1), 45.
- Goossens, R., & Snijders, C. (1995). Design criteria for the reduction of shear forces in beds and seats. *Journal of biomechanics*, 28(2), 225-230. doi:10.1016/0021-9290(94)00052-6
- Gregghi, F., Rossi, N., Souza, G., & Menegon, L. (2012). Contributions from the activity analysis to the products development project: case study based on a project of innovation and comfort in aircraft's cabins. *WORK*, 41(Supplement 1), 55-60. doi:doi.org/10.3233/WOR-2012-0135-55

- Groenesteijn, L., Vink, P., Looze, M.d., & Krause, F. (2009). Effects of differences in office chair controls, seat and backrest angle design in relation to tasks. *Applied ergonomics*, 40(3), 362-370. doi:10.1016/j.apergo.2008.11.011
- Grote, L., & Zou, D. (2017). Pulse Wave Analysis During Sleep. In *Principles and Practice of Sleep Medicine* (6th edition ed., pp. 1624-1632). Philadelphia, Pennsylvania, USA: Elsevier. doi:doi.org/10.1016/B978-0-323-24288-2.00167-7
- Guignard, J., & McCauley, M. (1990). The accelerative stimulus for motion sickness. In G.H. Crampton (Ed.), *Motion and space sickness* (pp. 123-152). Boca Raton, FL, USA: CRC Press.
- Haex, B. (2004). *Back and bed: ergonomic aspects of sleeping*. Boca Raton, FL, USA: CRC press. doi:10.1201/9780203022306
- Hansen, J.H., & Holmen, I.M. (2011). Sleep disturbances among offshore fleet workers. A questionnaire-based survey. *International maritime health*, 62(2), 123-130.
- Harrison, A.A., Sommer, R., Struthers, N., & Hoyt, K. (1986). *Implications of Privacy Needs and Interpersonal Distancing Mechanisms for Space Station Design*. (CR-177097 19860019510). Moffett Field, CA, USA: NASA, NASA-Ames Research Center. Retrieved from <https://ntrs.nasa.gov/citations/19860019510>.
- Hayashi, M., & Abe, A. (2008). Short daytime naps in a car seat to counteract daytime sleepiness: The effect of backrest angle. *Sleep and Biological Rhythms*, 6(1), 34-41.
- He, Z., & Vink, P. (2020). Aircraft interior requirements for a good sleep. *Journal of Ergonomics*, 10(3). doi:10.35248/2165-7556.20.10.261
- Hedge, A., Khalifa, H.E., & Zhang, J. (2009). On the control of environmental conditions using personal ventilation systems. Paper presented at the Human Factors and Ergonomics Society 53rd annual meeting. doi:10.1177/154193120905300811
- Hiemstra-van Mastrigt, S. (2015). *Comfortable passenger seats: Recommendations for design and research*. (Doctoral dissertation), Delft University of Technology, Delft, The Netherlands. doi:10.4233/uuid:eedd25e6-c625-45e9-9d32-f818aa89c19d
- Hilditch, C.J., & McHill, A.W. (2019). Sleep inertia: current insights. *Nature and science of sleep*, 155-165. doi:10.2147/NSS.S188911
- Hugon-Duprat, C., & O'Connell, J.F. (2015). The rationale for implementing a premium economy class in the long haul markets: Evidence from the transatlantic market. *Journal of Air Transport Management*, 47, 11-19. doi:10.1016/j.jairtraman.2015.03.005
- Huysmans, T., Goto, L., Molenbroek, J.F.M., & Goossens, R.H.M. (2020). DINED Mannequin. *Tijdschrift voor Human Factors*, 45(1), 4-7.
- Jay, S.M., Aisbett, B., Sprajcer, M., & Ferguson, S.A. (2015). Sleeping at work: not all about location, location, location. *Sleep Medicine Reviews*, 19, 59-66. doi:10.1016/j.smr.2014.04.003
- Ji, P., Huang, Y., & Zhou, Q. (2017). Mechanisms of using knee bolster to control kinematical motion of occupant in reclined posture for lowering injury risk. *International journal of crashworthiness*, 22(4), 415-424. doi:10.1080/13588265.2016.1275430
- Jonsson, B. (1978). Kinesiology: with special reference to electromyographic kinesiology. *Electroencephalography and clinical neurophysiology. Supplement*(34), 417-428.

- Jørgensen, K., Fallentin, N., Krogh-Lund, C., & Jensen, B. (1988). Electromyography and fatigue during prolonged, low-level static contractions. *European journal of applied physiology and occupational physiology*, 57, 316-321.
- Joshi, A., Kale, S., Chandel, S., & Pal, D.K. (2015). Likert scale: Explored and explained. *British journal of applied science & technology*, 7(4), 396. doi:10.9734/BJAST/2015/14975
- Kahneman, D., Fredrickson, B.L., Schreiber, C.A., & Redelmeier, D.A. (1993). When more pain is preferred to less: Adding a better end. *Psychological science*, 4(6), 401-405.
- Kaida, K., Takahashi, M., Åkerstedt, T., Nakata, A., Otsuka, Y., Haratani, T., & Fukasawa, K. (2006). Validation of the Karolinska sleepiness scale against performance and EEG variables. *Clinical neurophysiology*, 117(7), 1574-1581. doi:10.1016/j.clinph.2006.03.011
- Kawabata, A., & Tokura, H. (1996). Effects of two kinds of pillow on thermoregulatory responses during night sleep. *Applied Human Science*, 15(4), 155-159. doi:10.2114/jpa.15.155
- Kim, W., Jeon, E., Kim, G., Yeo, D., & Kim, S. (2022). Take-Over Requests after Waking in Autonomous Vehicles. *Applied Sciences*, 12(3), 1438. doi:10.3390/app12031438
- Kuo, C.W., & Jou, R.C. (2017). Willingness to pay for airlines' premium economy class: The perspective of passengers. *Journal of Air Transport Management*, 59, 134-142. doi:10.1016/j.jairtraman.2016.12.005
- Kwon, J.Y., Kim, J.K., Lee, H., Lee, D., & Ju, D.Y. (2023). A Comprehensive Overview of Basic Research on Human Thermal Management in Future Mobility: Considerations, Challenges, and Methods. *Sustainability*, 15(9), 7335. doi:10.3390/su15097335
- Law, T. (2013). Brain Cooling. In *The Future of Thermal Comfort in an Energy-Constrained World* (pp. 53-82): Springer Cham. doi:10.1007/978-3-319-00149-4
- Lee, S.Y., & Brand, J.L. (2005). Effects of control over office workspace on perceptions of the work environment and work outcomes. *Journal of Environmental Psychology*, 25(3), 323-333. doi:10.1016/j.jenvp.2005.08.001
- Lewis, L., Patel, H., Cobb, S., D'cruz, M., Bues, M., Stefani, O., & Grobler, T. (2016). Distracting people from sources of discomfort in a simulated aircraft environment. *WORK*, 54(4), 963-979. doi:10.3233/WOR-162356
- Lin, Z., & Deng, S. (2008). A study on the thermal comfort in sleeping environments in the subtropics—developing a thermal comfort model for sleeping environments. *Building and Environment*, 43(1), 70-81. doi:10.1016/j.buildenv.2006.11.026
- Liu, J., Yu, S., & Chu, J. (2019). The passengers' comfort improvement by sitting activity and posture analysis in civil aircraft cabin. *Mathematical Problems in Engineering*, 2019, 1-10. doi:10.1155/2019/3278215
- Luo, M., Cao, B., Zhou, X., Li, M., Zhang, J., Ouyang, Q., & Zhu, Y. (2014). Can personal control influence human thermal comfort? A field study in residential buildings in China in winter. *Energy and Buildings*, 72, 411-418. doi:10.1016/j.enbuild.2013.12.057
- Matsangas, P., & Shattuck, N.L. (2017). Exploring sleep-related habitability issues in berthing spaces on US Navy ships. Paper presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting.

- Matsangas, P., & Shattuck, N.L. (2021). Habitability in berthing compartments and well-being of sailors working on US Navy surface ships. *Human factors*, 63(3), 462-473. doi:10.1177/0018720820906050
- Matsangas, P., Shattuck, N.L., & McCauley, M.E. (2015). Sleep duration in rough sea conditions. *Aerospace medicine and human performance*, 86(10), 901-906. doi:10.3357/AMHP.4250.2015
- Matsumoto, Y., Kanamaru, M., Tan, P.X., & Kamioka, E. (2023). Clarifying Optimum Setting Temperatures for In-Flight Personal Air Conditioning System Considering Individual Thermal Sensitivity Characteristics. *Electronics*, 12(371). doi:10.3390/electronics12020371
- Mazari, F.B., Chotebor, M., Naeem, J., Mazari, A., & Havelka, A. (2016). Effect of perforated polyurethane foam on moisture permeability for car seat comfort. *Fibres & Textiles in Eastern Europe*, 24(6), 165-169. doi:10.5604/12303666.1221752
- Melikov, A., Ivanova, T., & Stefanova, G. (2012). Seat headrest-incorporated personalized ventilation: Thermal comfort and inhaled air quality. *Building and Environment*, 47, 100-108. doi:10.1016/j.buildenv.2011.07.013
- Mergl, C. (2006). *Entwicklung eines Verfahrens zur Objektivierung des Sitzkomforts auf Automobilsitzen*. (Doctoral dissertation), Technische Universität München, München, Germany. Retrieved from <https://d-nb.info/980332915/34>
- Molenbroek, J.F.M., Albin, T.J., & Vink, P. (2017). Thirty years of anthropometric changes relevant to the width and depth of transportation seating spaces, present and future. *Applied ergonomics*, 65, 130-138. doi:10.1016/j.apergo.2017.06.003
- Molenbroek, J.F.M., Groothuizen, T.J.J., & de Bruin, R. (2011). Design for all: Not excluded by design. In J.F.M. Molenbroek, J. Mantas, & R. de Bruin (Eds.), *A friendly rest room: developing toilets of the future for disabled and elderly people* (pp. 7-18): IOS Press. doi:10.3233/978-1-60750-752-9-7
- Molenbroek, J.F.M., Jürgens, H., Houtkamp, J.J., Burger, A.K.C., Steenbekkers, L.P.A., Dirken, J.M., . . . Huysmans, T. (1984-2020). *DINED Anthropometric Database*. gdw1984, delstu1986, kima1993, geron1998, CAESAR, Goto (2011) Children's Heads, delstu2016, chile2016-workers. Retrieved from: <https://dined.io.tudelft.nl/>
- Müller, B., Lindner, A., Norrefeldt, V., Song, Y., Mansfield, N., & Vink, P. (2022). Measurement of noise and indoor climate on board a turboprop airplane flight.
- Naddeo, A., Cappetti, N., Califano, R., & Vallone, M. (2015). The role of expectation in comfort perception: the mattresses' evaluation experience. *Procedia Manufacturing*, 3, 4784-4791.
- Naddeo, A., Cappetti, N., Vallone, M., & Califano, R. (2014). New trend line of research about comfort evaluation: proposal of a framework for weighing and evaluating contributes coming from cognitive, postural and physiologic comfort perceptions. Paper presented at the Advances in Social and Organizational Factors, Edited by Peter Vink, Published By "Advances in Human Factors and Ergonomics" Conference.
- Nemcokova, R., Glombikova, V., & Komarkova, P. (2023). Transport of Moisture in Car Seat Covers. *AUTEX Research Journal*, 23(3), 381-387. doi:10.2478/aut-2022-0017
- Nicholls, M. (2023). *The Importance of "Thermal Comfort" in the overall passenger experience*. Tapis Corporation. Presentation at the Aircraft Cabin Innovation Summit EU 2023 on 22 March 2023, Hamburg, Germany.

- Nicholson, A., & Stone, B.M. (1987). Influence of back angle on the quality of sleep in seats. *Ergonomics*, 30(7), 1033-1041.
- Pang, L., Qin, Y., Liu, D., & Liu, M. (2014). Thermal comfort assessment in civil aircraft cabins. *Chinese Journal of Aeronautics*, 27(2), 210-216.
- Roach, G.D., Matthews, R., Naweed, A., Kontou, T.G., & Sargent, C. (2018). Flat-out napping: The quantity and quality of sleep obtained in a seat during the daytime increase as the angle of recline of the seat increases. *Chronobiology international*, 35(6), 872-883. doi:10.1080/07420528.2018.1466801
- Robinette, K.M., Blackwell, S., Daanen, H., Boehmer, M., & Fleming, S. (2002). *Civilian American and European Surface Anthropometry Resource (Caesar), Final Report, Volume 1: Summary*. United States Air Force Research Laboratory, Ohio, USA. Retrieved from <https://www.humanics-es.com/CAESARvol1.pdf>.
- Roelofsen, C.P.G. (2016). *Modelling relationships between a comfortable indoor environment, perception and performance change*. (PhD Thesis), Delft University of Technology, Delft. doi:10.4233/uuid:e7778a5c-3013-40ed-9567-bceaffc57ab9
- Rooszendaal, T., Verwaal, M., Buso, A., Scharff, R.B., Song, Y., & Vink, P. (2022). Development of a Soft Robotics Module for Active Control of Sitting Comfort. *Micromachines*, 13(3), 477.
- Rosekind, M.R., Gregory, K.B., Co, E.L., Miller, D.L., & Dinges, D.F. (2000). Crew factors in flight operations XII: A survey of sleep quantity and quality in on-board crew rest facilities. Retrieved from
- Samn, S.W., & Perelli, L.P. (1982). *Estimating aircrew fatigue: a technique with application to airlift operations*. (SAM-TR-82-21). Texas, USA: USAF School of Aerospace Medicine. Retrieved from <https://apps.dtic.mil/sti/pdfs/ADA125319.pdf>.
- Schifferstein, H.N., & Hekkert, P. (2011). *Product experience*: Elsevier.
- Shah, P.B., & Luximon, Y. (2021). Assessment of pressure sensitivity in the head region for Chinese adults. *Applied ergonomics*, 97, 103548. doi:10.1016/j.apergo.2021.103548
- Sjøgaard, G., Kiens, B., Jørgensen, K., & Saltin, B. (1986). Intramuscular pressure, EMG and blood flow during low-level prolonged static contraction in man. *Acta Physiologica Scandinavica*, 128(3), 475-484.
- Smulders, M. (2018). *Flex and relax: An exploration on headrest design for sleeping and watching IFE in premium aircraft seats*. (Industrial Design Engineering Master thesis), Delft University of Technology, Delft. Retrieved from <http://resolver.tudelft.nl/uuid:4e929659-63d7-4816-82b0-a35cd20725ea>
- Smyth, J., Jennings, P., & Birrell, S. (2020). Are You Sitting Comfortably? How Current Self-driving Car Concepts Overlook Motion Sickness, and the Impact It Has on Comfort and Productivity. Paper presented at the Advances in Human Factors of Transportation: Proceedings of the AHFE 2019 International Conference on Human Factors in Transportation, July 24-28, 2019, Washington DC, USA 10.
- Smyth, J., Robinson, J., Burridge, R., Jennings, P., & Woodman, R. (2021). Towards the Management and Mitigation of Motion Sickness—An Update to the Field. Paper presented at the Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021) Volume III: Sector Based Ergonomics.

- Stanglmeier, M.J., Paternoster, F.K., Paternoster, S., Bichler, R.J., Wagner, P.-O., & Schwirtz, A. (2020). Automated driving: A biomechanical approach for sleeping positions. *Applied ergonomics*, 86, 103103.
- Stevens, S.C., & Parsons, M.G. (2002). Effects of motion at sea on crew performance: a survey. *Marine technology and SNAME news*, 39(01), 29-47. doi:10.5957/mt.2002.39.1.29
- Sunde, E., Bråtveit, M., Pallesen, S., & Moen, B.E. (2016). Noise and sleep on board vessels in the Royal Norwegian Navy. *Noise and Health*, 18(81), 85-92. doi:10.4103/1463-1741.178481
- Suzuki, H., Shiroto, H., & Tezuka, K. (2005). Effects of low frequency vibration on train motion sickness. *Quarterly Report of RTRI*, 46(1), 35-39.
- Tang, L., & Liu, J. (2012). Safety analysis of belted occupant in reclining seat. *International journal of vehicle design*, 60(1/2), 39-56.
- Tang, L., Zheng, J., & Zhou, Q. (2020). Investigation of risk factors affecting injuries in reclining seat under frontal impact. *International journal of vehicle safety*, 11(3), 247-274.
- Troester, M.M., Quan, S.F., Berry, R.B., Plante, D.T., Abreu, A.R., Alzoubaidi, M., . . . Thomas, S.M. (2023). *The AASM Manual for Scoring of Sleep and Associated Events: Rules, Terminology and Technical Specifications*. In.
- Van der Grinten, M.P., & Smitt, P. (1992). Development of a practical method for measuring body part discomfort. *Advances in industrial ergonomics and safety*, 4(635), 311-318.
- van Deun, D., Verhaert, V., Willemsen, T., Wuyts, J., Verbraecken, J., Exadaktylos, V., . . . Vander Sloten, J. (2012). Biomechanics-based active control of bedding support properties and its influence on sleep. *WORK*, 41(Supplement 1), 1274-1280. doi:10.3233/WOR-2012-0313-1274
- van Dijk, L., Keesmaat, P., Ligtenberg, G., Smulders, M., & Huysmans, T. (2021). *Evaluating the effectiveness of the 'head, face and neck pressure sensitivity model' for long-term comfort [WP2]*. Delft University of Technology. Delft, The Netherlands.
- Verhaert, V., Haex, B., Wilde, T.D., Berckmans, D., Verbraecken, J., Valck, E.d., & Sloten, J.V. (2011). Ergonomics in bed design: the effect of spinal alignment on sleep parameters. *Ergonomics*, 54(2), 169-178.
- Vink, P. (2004). *Comfort and design: principles and good practice*. Boca Raton, Florida, USA: CRC Press. doi:doi.org/10.1201/9781420038132
- Vink, P., Anjani, S., Udomboonyanupap, S., Torkashvand, G., Albin, T., Miguez, S., . . . Vanacore, A. (2021). Differences and similarities in comfort and discomfort experience in nine countries in Asia, the Americas and Europe. *Ergonomics*, 64(5), 553-570. doi:10.1080/00140139.2020.1853248
- Vink, P., & Brauer, K. (2011). *Aircraft Interior Comfort and Design*. Boca Raton, FL, USA: CRC Press. doi:10.1201/b10815
- Vink, P., & Hallbeck, S. (2012). Editorial: Comfort and discomfort studies demonstrate the need for a new model. *Applied ergonomics*, 43(2), 271-276. doi:10.1016/j.apergo.2011.06.001
- Vink, P., Porcar-Seder, R., de Pozo, Á.P., & Krause, F. (2007). Office chairs are often not adjusted by end-users. Paper presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting.

- Vledder, G., Compomanes, R.S., Singh, U., Kiliç, H., Smulders, M., Song, Y., & Vink, P. (2024). Experiences of upright sleeping in a vehicle: the preferred back rest angle. *Advances in Human Factors of Transportation*, 148(148). doi:10.54941/ahfe1005258
- Vogelpohl, T., Kühn, M., Hummel, T., & Vollrath, M. (2019). Asleep at the automated wheel—Sleepiness and fatigue during highly automated driving. *Accident Analysis & Prevention*, 126, 70-84.
- Wegner, M.B. (2020). *Seat Comfort Objectification: A new approach to objectify the seat comfort*. (PhD thesis), Delft University of Technology, Delft, The Netherlands.
- Wiechel, J., & Bolte, J. (2006). Response of Reclined Post Mortem Human Subjects to Frontal Impact (0148-7191). Retrieved from
- Xin, Y., Cui, W., & Zeng, J. (2019). Experimental study on thermal comfort in a confined sleeping environment heating with capillary radiation panel. *Energy and Buildings*, 205, 109540.
- Zenk, R. (2008). *Objektivierung des Sitzkomforts und seine automatische Anpassung*. (Doctoral dissertation), Technische Universität München, München, Germany. Retrieved from <https://mediatum.ub.tum.de/doc/656298/>
- Zenk, R., Franz, M., Bubb, H., & Vink, P. (2012). Spine loading in automotive seating. *Applied ergonomics*, 43(2), 290-295. doi:10.1016/j.apergo.2011.06.004
- Zhang, H., Meng, L., Gong, Y., & Wang, N. (2021). The influence of backrest angles on the passenger neck comfort during sleep in the economy class air seat without head support. *International Journal of Industrial Ergonomics*, 84, 103074.
- Zhang, Y.F., Wyon, D.P., Fang, L., & Melikov, A.K. (2007). The influence of heated or cooled seats on the acceptable ambient temperature range. *Ergonomics*, 50(4), 586-600. doi:10.1080/00140130601154921

ACKNOWLEDGEMENTS

In a big project such as a PhD, you need the help of many others. Therefore I would like to thank the following people for their support and contribution during the past years.

First and foremost, my promotors Peter Vink and Yu (Wolf) Song.

Anyone can consider themselves lucky when they had the pleasure to work with Peter. With your contagious enthusiasm you have motivated me, even through the toughest moments. And every time I could not find that ones obscure article needed, I could count on your encyclopaedic knowledge. Thank you Peter, for sparking the interest for science and research during my Master study, and offering me the opportunity to continue at the TU Delft first as a lecturer/researcher, later as a full-time PhD candidate, and mentoring me the past decade. I learned a lot from you.

Thank you Wolf for all your tremendous help and counsel in so many situations (such as advising on how to set-up a Master course, giving a late-night crash course computer building (together with other PhD's), and prototyping study setups with Python) even at ridiculous hours. Thank you for always making time and mentoring me in both research and education.

This PhD would not have been possible without the major funding provided by BMW Group AG; thank you for your generosity.

Dear members of the doctoral committee; thank you for taking the time to read my dissertation, your feedback and being part of my committee. I have had the pleasure to collaborate with most of you the past years at conferences, on research and in education. Thank you for sharing your knowledge and all your advice.

I would like to thank my co-authors and research collaborators/supporters for thinking along, executing/supporting experiments and/or co-writing: Iolanda Fiorillo, Karlien Berghman, Lianne van Dijk, Toon Huysmans, Shabila Anjani, Gerbera Vledder, Allesandro Naddeo, Silvana Piro, Halil Kılıç, Chiara Percuoco, Liliana Di Brigida, Sagar Dungal, Udo Schultheis, Elmer van Grondelle, Justin Kane, Kashyap Krishna, Nicola Capetti, Marloes Koenraads, Terence Carter and Tom Albin. A very special thanks to Bertus Naagen, who helped me a lot in research and education, and was always in for some fun and lunches with colleagues and PhD candidates. In particular I would like to thank two people who supported me in the beginning of my (academic) career; Joyce Bouwens as former Zodiac, TU Delft and fellow PhD colleague and Suzanne Hiemstra-van Mastriht as TU Delft colleague. Joyce: thank you for all the lovely conversations and your straight to the point advice. Suzanne: thank you for all your advice, our collaborations, fun talks and for being such a great roommate.

For supporting and/or funding studies I would like to thank:

Safran (formerly Zodiac Aerospace), with a special thanks to dr. Udo Schultheis for providing multiple project opportunities. My former Zodiac colleagues Jochem, Jenny,

Paul, Tom, Foek and Jeff; thank you for welcoming me, all the lovely conversations and your support in my research and design work. A very special thanks to Rusty; thank you for your support in research and leading the team through challenging times.

Crescent Tech B.V. and the NWO, with a special thanks to Patrick Keesmaat and Samy Andary, for the collaboration on the head sensitivity study and related projects.

Vanema and Studio Moderna, with a special thanks to Boris Ribicic for the collaboration on the foam-spring study.

I would also like to thank my colleagues at the Sustainable Design Engineering department, with a special mention to those with whom I've collaborated in education and research: Doris Aschenbrenner, Helen Yuan, Xinhe Yao, Irene Fernandez Villegas, Sepideh Ghodrath, Job Kneppers, Wasabii Ng, Alice Busso, Maximilan Wegner, Michelle Kuipers, Bas Flipsen and Arjen Jansen. A very special thanks to Caroline Kroon and Jos Oberdorf for their indispensable help in developing Master education. Thank you Selina, Rafaela, Mariska, Sara, Sylvia and Jolanda for all the lovely talks and your support.

Furthermore, I would like to thank my colleagues at the Human-Centered Design department, with a special mention to those with whom I've collaborated in education and research: Marijke Melles, Gonny Hoeksta, Johan Molenbroek, Marian Loth, Lyè Goto, Meng Li, Sumalee Udomboonyanupap, Karina Kirk Driller and Richard Goossens. With a very special thanks to Marijke Dekker for your tremendous support in developing Master education. Thank you Denise, Daphne and Charleyne for your support.

I would also like to thank my PhD mentor Sacha Silvester; for your mentorship and council the first two years of my PhD.

Thank you Eveline Heesterbeek (MD) for your consulting on medical safety in our research.

Many thanks to all the supporting staff at the faculty of Industrial Design Engineering, without whom my work at the TU Delft would not have been possible; the Model Making and Machine Lab (PMB), Applied Labs, Logistic Point, FMVG, ServicePoint and the cleaning staff. I also want to thank the HREC for ethical review of research, with a special mention to safety expert Peter Kohne for reviewing many of our experiments.

Thank you Dolores Hilhorst for your unlimited support, cheering me on and all the proofreading the past four years.

A special thanks to my paranymphs Wendy van der Horst and Bram van der Grinten; for supporting me during my PhD defense ceremony.

Last but not least, I'd like to thank my friends and family for their support; Rineke & Norman (thank you for the native-speaker language support), Thekla, Mercedes, Karin, Evelien & Pepijn, Rafael, Lisa, Florian, Alexander, Marinus and Gina. With a special mention to my superhero grandma W.M.T. Smulders-Mokveld, my parents Annemarie and Ruud, and my brother Sam; thank you for your enormous support – I could not have done this without you.

ABOUT THE AUTHOR



Photo by Esther Erkelens

Maxim Smulders was born on September 12, 1991 in Delft, the Netherlands. In 2010 he finished secondary school (Grotius College, Delft) and subsequently studied Industrial Design Engineering at the Delft University of Technology. After obtaining his Bachelor's degree with a Minor in Architecture, he continued with the Master Integrated Product Design. During his Master, Maxim specialised on physical ergonomics and comfort. In 2018, he graduated on the topic of improving the comfort experience for watching IFE and sleeping in premium aircraft seats through a headrest design.

During his studies Maxim conducted a multitude of design and research projects in the aviation and office-furniture industry on seating, comfort, user-friendliness and safety, both in the Netherlands and Texas, USA. As a student assistant he was involved in various comfort studies under the supervision of prof.dr. Peter Vink. He was also involved in setting up the EurErg@IDE education program for Master students at IDE under the supervision of dr.ir. Marijke Melles and in collaboration with Human Factors NL and the SRe (Foundation for Registration of Ergonomists). This program helps Master students to specialise on ergonomics and obtain a certificate that proves that their education complies with the training requirements for the CREE registration as an European Ergonomist.

Right after his graduation, Maxim started as a lecturer and researcher on *'Technical Ergonomics'* at the Sustainable Design Engineering department of the TU Delft faculty of Industrial Design Engineering. In this position he supervised and supported Master and PhD students on design and research projects, with a special interest in vehicle interior comfort, ergonomics and sleep. He was also course coordinator of *'Technology for Concept Design'* and lectured on e.g. 3D scanning and Technology Readiness Levels for industrial design. After his three-year term he focussed his attention on his own research; as a PhD candidate he has been specialising on the topic of *'Seating and sleeping comfort in transit'*. Since the summer of 2021 he is also editor of the journal *'Tijdschrift voor Human Factors'* (journal on Human Factors) at Human Factors NL (the Dutch ergonomics association).

As of December 2023, Maxim is a Human Factors Designer at Luchtverkeersleiding Nederland (LVNL; Air Traffic Control Netherlands).

Curriculum Vitae

Work experience	(selection; please see LinkedIn for full work experience)
2023 – Present	Human Factors Designer <i>TO-Design & Continuation Training department, Air Traffic Control Netherlands (LVNL) Schiphol, The Netherlands</i>
2018 – 2024	PhD candidate on ‘Seating and sleeping comfort in transit’ <i>Sustainable Design Engineering department, Industrial Design Engineering, TU Delft Delft, The Netherlands</i>
2018 – 2021	Lecturer Technical Ergonomics <i>Sustainable Design Engineering department, Industrial Design Engineering, TU Delft Delft, The Netherlands</i>
2017 – 2018	Teaching Assistant (Ergonomics Education) <i>Human Centred Design department, Industrial Design Engineering, TU Delft Delft, The Netherlands</i>
2017	Research Assistant (Comfort Research) <i>Sustainable Design Engineering department, Industrial Design Engineering, TU Delft Delft, The Netherlands</i>
2016	Trainee Human Factors and Ergonomics <i>Human factors and Ergonomics department, Zodiac Seats US, Zodiac Aerospace (now Safran Group) Gainesville, Texas, U.S.A.</i>
2015 – 2016	Intern Research & Technology <i>Research & Technology department, Zodiac Galleys and Equipment, Zodiac Aerospace Alkmaar, The Netherlands</i>

Education

- 2018 – 2024 **PhD Industrial Design Engineering**
Faculty of Industrial Design Engineering, TU Delft
Delft, The Netherlands
- 2013 – 2018 **MSc. Integrated Product Design**
Faculty of Industrial Design Engineering, TU Delft
Delft, The Netherlands
- 2010 – 2013 **BSc. Industrial Design Engineering**
Faculty of Industrial Design Engineering, TU Delft
Delft, The Netherlands

Voluntary work

- 2021 – Present **Editor**
Tijdschrift voor Human Factors, Human Factors NL
Arnhem, The Netherlands
- 2020 – Present **First Aid Responder / Public Health Aid / Logistics /
Location coordinator a.i.**
Rode Kruis Nederland
Delft/The Hague, The Netherlands

Contact details

LinkedIn: [linkedin.com/in/maxim-smulders](https://www.linkedin.com/in/maxim-smulders)
ResearchGate: [researchgate.net/profile/Maxim-Smulders](https://www.researchgate.net/profile/Maxim-Smulders)
ORCID: 0000-0001-9957-0991

LIST OF PUBLICATIONS

Publications part of this dissertation

Journal publications

Smulders, M., Berghman, K., Koenraads, M., Kane, J. A., Krishna, K., Carter, T. K., & Schultheis, U. (2016). Comfort and pressure distribution in a human contour shaped aircraft seat (developed with 3D scans of the human body). *Work*, 54(4), 925-940.

Smulders, M., Naddeo, A., Cappetti, N., van Grondelle, E. D., Schultheis, U., & Vink, P. (2019). Neck posture and muscle activity in a reclined business class aircraft seat watching IFE with and without head support. *Applied ergonomics*, 79, 25-37.

Dangal, S., Smulders, M., & Vink, P. (2021). Implementing spring-foam technology to design a light weight and comfortable aircraft seat-pan. *Applied Ergonomics*, 91, 103174.

Smulders, M., & Vink, P. (2021). Human behaviour should be recorded in (dis)comfort research. *Work*, 68(s1), S289-S294.

Smulders, M., van Dijk, L. N. M., Song, Y., Vink, P., & Huysmans, T. (2023). Dense 3D pressure discomfort threshold (PDT) map of the human head, face and neck: A new method for mapping human sensitivity. *Applied ergonomics*, 107, 103919.

Conference papers

Vink, P., Anjani, S., Smulders, M., & Hiemstra-van Mastrigt, S. (2017). Comfort and discomfort effects over time: the sweetness of discomfort and the pleasure towards of the end. In *1st International Comfort Congress*, Salerno, Italy.

Smulders, M., Naddeo, A., Cappetti, N., van Grondelle, E.D., Schultheis, U.W., & Vink, P. (2017) Neck posture and muscle activity with and without head support in a reclined sitting posture when watching IFE. In *1st International Comfort Congress* (pp. 1-10), Salerno, Italy.

Smulders, M., & Vink, P. (2021). Sleep quality and (dis) comfort in minimal space envelope. In *3rd International Comfort Congress 2021*, Delft, The Netherlands.

Smulders, M., & Vink, P. (2022). Sleeping postures in adults: a literature review. In *21st Triennial Congress of the International Ergonomics Association*, Vancouver, Canada.

Book chapters

Hiemstra-van Mastrigt*, S., Smulders*, M., Bouwens, J. M., & Vink, P. (2019). Designing aircraft seats to fit the human body contour. In *DHM and Posturography* (pp. 781-789). Academic Press. *Shared first author.

Other publications (2015-2024)

Journal publications

Piro, S., Fiorillo, I., Anjani, S., Smulders, M., Naddeo, A., & Vink, P. (2019). Towards comfortable communication in future vehicles. *Applied Ergonomics*, 78, 210-216.

Fiorillo, I., Piro, S., Anjani, S., Smulders, M., Song, Y., Naddeo, A., & Vink, P. (2019). Future vehicles: the effect of seat configuration on posture and quality of conversation. *Ergonomics*, 62(11), 1400-1414.

Dutch publications

Smulders, M., & Hogeweg, A. (2022). Human Factors en octrooien retainment assembly: Retainment assembly Octrooi US11167926 (B2). *Tijdschrift voor Human Factors*, 47(1), 25.

Wiezer, N., Smulders, M., & Henkemans, O. B. (2022). Het tijdschrift nu en in de toekomst. *Tijdschrift voor Human Factors*, 47(2), 18-19.

Conference papers

Fiorillo, I., Song, Y., Smulders, M., Vink, P., & Naddeo, A. (2021). Flat cushion vs Shaped cushion: comparison in terms of pressure distribution and postural perceived discomfort. In *Congress of the International Ergonomics Association* (pp. 247-254). Cham: Springer International Publishing.

Vink, P., Singh, U., Smulders, M., Vledder, G., Yao, X., & Song, Y. (2023, October). Back rest angle influence on nap quality and comfort. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 67(1), 316-320. Sage CA: Los Angeles, CA: SAGE Publications.

Vink, P., Vledder, G., Smulders, M., & Song, W. (2023). Preferred environmental conditions and products for comfortable nap in vehicles. In *4th International Comfort Congress* (p. 104), Amberg, Germany.

Vledder, G., Compomanes, R. S., Singh, U., Kılıç, H., Smulders, M., Song, Y., & Vink, P. (2024). Experiences of upright sleeping in a vehicle: the preferred back rest angle. *Advances in Human Factors of Transportation*, 148(148).

Thesis

Smulders, M. (2018). Flex and relax: an exploration on headrest design for sleeping and watching IFE in premium aircraft seats. (Master thesis) Delft University of Technology, Delft, The Netherlands.

Presentations

Smulders, M. (2017) How (not) to 3D scan for passenger seat design. IDE-Masterclass Vehicle Seat Comfort and Design, Delft University of Technology, Delft, The Netherlands (Invited speaker).

Workshops

Vink, P., & Smulders, M. (2016) Towards a light weight seat with optimum comfort. IQPC Innovative Seating Conference 2016, Düsseldorf, Germany. (Workshop)

Posters

Smulders, M. (2015) Galley Challenges: qualitative research insights from five FA's of KLM and Ryanair and seven caterers of Gate Gourmet and KCS. Poster presented at Zodiac Galleys Europe, Alkmaar, The Netherlands. (Poster)

Patents

Vlaming, P.C., & Smulders, M. (2019) Retainment assembly (World Intellectual Property Organisation, WO2020018698A1; United States of America, US11167926B2). U.S. Patent and Trademark Office.

