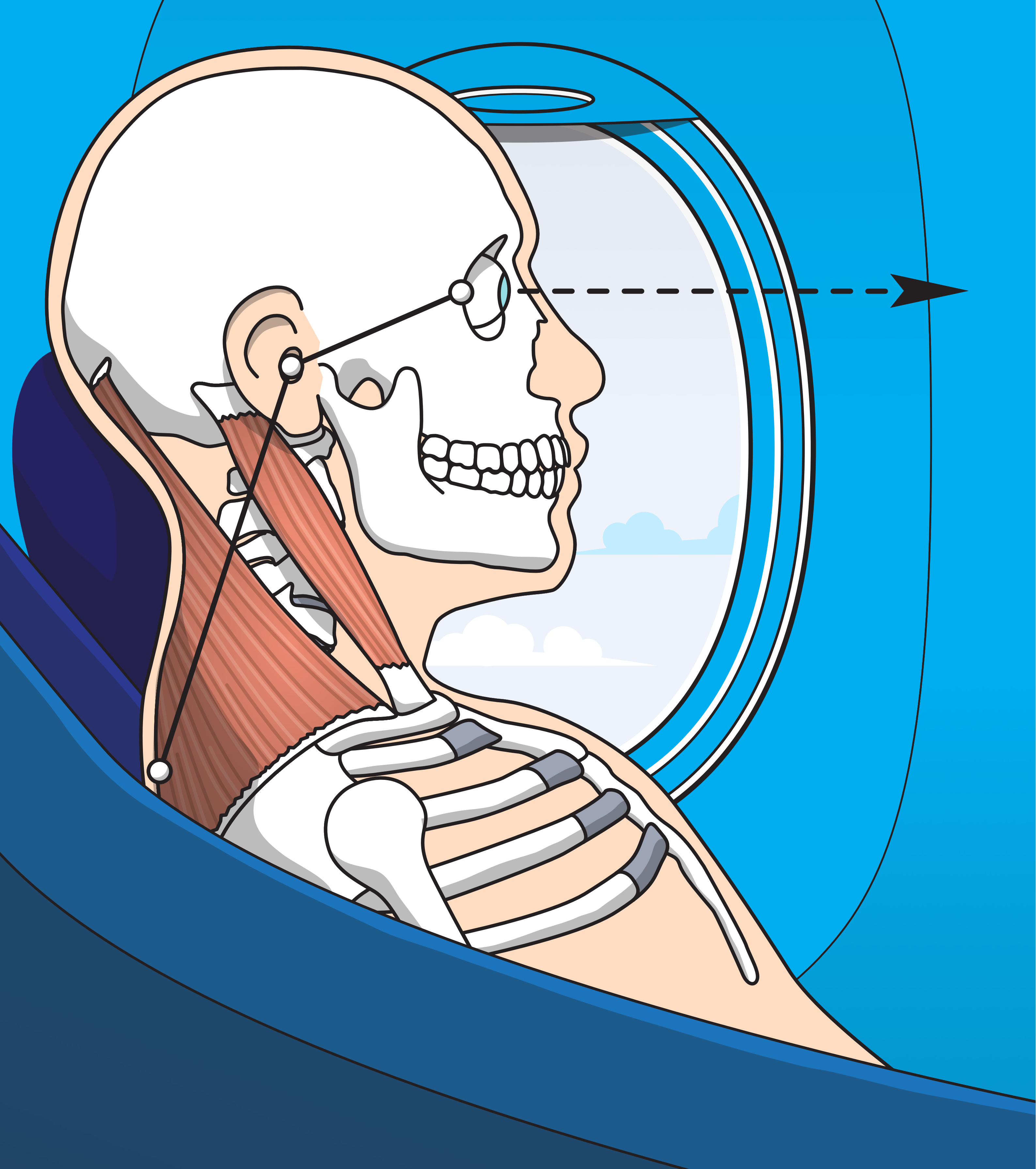
Maxim Smulders

Flex and relax

an exploration on headrest design



Flex and relax

An exploration on headrest design for sleeping and watching IFE in premium aircraft seats

Analysis, research, insights and design

a master graduation thesis

Maxim Smulders
Master graduate Integrated Product Design

Industrial Design Engineering
Delft University of Technology
Landbergstraat 15
2628CE Delft
The Netherlands

in order to obtain the degree of *Ingenieur*/*Master of Science*

under supervision of

Prof.dr. Peter Vink
Professor Environmental Ergonomics, TU Delft

BA Elmer van Grondelle MBA
Assistant Professor, TU Delft

IFE research in cooperation with

Prof.dr. Alessandro Naddeo M.D.
Department of Industrial Engineering, University of Salerno

Prof. Nicola Cappetti
Department of Industrial Engineering, University of Salerno

Dr. Udo Schultheis,
Driver Performance Researcher, General Motors
former Director Human Factors and Ergonomics, Zodiac Seats US

original project for

Human Factors and Ergonomics
Zodiac Seats US LLC
Zodiac Seats Division
Zodiac Aerospace

Over the Atlantic – to all the World . . .

IT'S A TREAT TO GO DUTCH

KLM *Royal* Dutch, of course! Wherever you fly KLM . . . to Europe or any other continent, you are welcomed aboard with the same warm friendliness. You experience the hospitality that has been traditional with the Dutch for centuries and is inherent in KLM today. This also holds true for any of KLM's 187 offices around the world, where English-speaking personnel take a personal interest in serving you . . . helping to make your trip *all* enjoyment. Fly KLM. You'll agree, "It's a Treat To Go Dutch."

SEE YOUR TRAVEL AGENT or KLM Royal Dutch Airlines – offices in principal cities of the United States and the rest of the world.

KLM
ROYAL DUTCH AIRLINES

World's First Airline

“

The seat is easily the most important ingredient in the airplane interior.

Make a man comfortable,
and everything looks rosy to him.
He can relax, his food tastes better,
the trip will seem hours shorter…

Henry Dreyfuss (1967) (as cited in Eisenbrand (2004))

🡐 KLM Royal Dutch Airlines (1956)

Executive summary

This master graduation thesis explores the possibilities for improving the comfort experience for watching in flight entertainment (IFE) and sleeping in a business class (BC) and premium economy class (PEC) aircraft seat trough (mainly) headrest design. See Figure E.1 for a full project overview. Experimental and extensive literature research on sleeping and watching IFE in transit results in design requirements and recommendations for the (aircraft) seating industry. The study on head support for watching IFE in a slouched posture resulted in a scientific publication in Applied Ergonomics. Further research and development is proposed of a premium economy headrest supporting for sleeping with a limited recline and head-neck support for watching IFE in premium cabins. In addition, the exploration of a highly personalised BC bed-seat is advised.

Sleeping full-flat in BC
The earlier mentioned focus on headrest design is less applicable on BC sleep. Here the focus should be on overall bed design and control features. Nevertheless, as new generation BC seats provide full flat sleeping capabilities, it is advised to level the headrest with the backrest when in full-flat mode (becoming a part of the mattress surface area) and provide a separate pillow based on the passengers choice. This gives passengers more freedom of posture and approximates the conditions passengers are used to at home, which is important to sleep quality. Also disturbing factors should be minimised as much as possible. This includes cabin services and belt checks.

One of the challenges BC passengers face is the lack of control over their own activities and environment within the cabin. A BC bed-seating concept is proposed which includes personal flight scheduling features, which gives BC passengers the option to opt in or out of services and schedule their own activities. Their choices will be communicated by displays outside the seat (e.g. non-disturb and seatbelt on sign) and in the galley. In addition, automated seatbelt checks prevent flight attendants (FA's) to wake BC passengers. This can improve passenger's sense of control and prevent unwanted disturbance by cabin crew.

In search of improving the bed-seat experience, it was found that the firmness per area of the seat should be adjusted according to the taken posture for proper support. When seated, firm support is needed at the pelvis region, as most of the body weight can be carried here. When sleeping lateral, that same area should soft, to allow the pelvis to sink for a straight alignment of the spine. In addition, anthropometric differences and preferences (e.g. firmness) require personal optimised support. Exploration of a bed-seat that can actively adapt to the taken posture by and anthropometrics of the passenger is advised.

Sleeping with limited recline in PEC
Sleeping with limited recline in PEC is challenging. Muscles relax when entering deep sleep, which causes the head slide, nod and fall. This triggers the sleep-wake system, waking up the passenger. Without adequate support of the head passengers will not be able to have a qualitative sleep, as they will not go trough deep sleep and REM cycles (which account for physical and mental recovery respectively). Two headrest designs are proposed which support the head by a jaw line on the side ‘wings’, as the load of the head can be carried here and prevent the head to fall and nod. One design iterates on existing headrests, requiring the addition of two rotational hinges and jaw-line support on the ‘wings’, allowing it to create a ‘bowl shape’ the head can rest in. Implementation might be relative simple, but further prototyping is advised. The other design is more radical, as it articulates sideways following natural movement of the head during sleep. When going sideways (over the Z-axis), the headrest turns (over the Y-axis) ’catching’ the head, preventing it of falling down. The mechanics to articulate this headrest are more challenging and require further research and development.

Watching IFE in premium cabins
People prefer to watch IFE and TV in a slouched posture (reclined backrest and leg support), as is possible in premium cabins like BC and PEC. In current aircraft seats passengers lack head/neck support, as they flex their head forward to have a perpendicular view on the IFE screen. Prolonged contraction of the neck and eye muscles to sustain view on the IFE screen (e.g. during multiple movies) may fatigue the muscles, lead to pains and discomfort.

Pillows offered in premium cabins may offer some support, but – depending on the thickness and material – may be insufficient. The scientific study in this thesis shows that head support improves the 'expected comfort' and may lower muscle tension in the neck as shown in an AnyBody™ simulation. This was however not validated by an EMG study, which showed no difference in major flexion and extension neck muscles. The discovery was that humans search for a neutral posture, with minimal strain on the musculoskeletal system. This could explain the lack of a significant difference. However, further research on the long-term (dis)comfort is advised. Nevertheless, a proposed design of a forward tilting headrest based on a simple friction hinge may be an interesting solution to improve passenger comfort when watching IFE.

This master thesis shows that through headrest design comfort of premium aircraft passengers can be improved for watching IFE and sleeping with limited recline. Aircraft seat manufacturers are therefore advised to further research and develop proposed headrest designs, as current headrest are insufficient and underexposed in seat design.

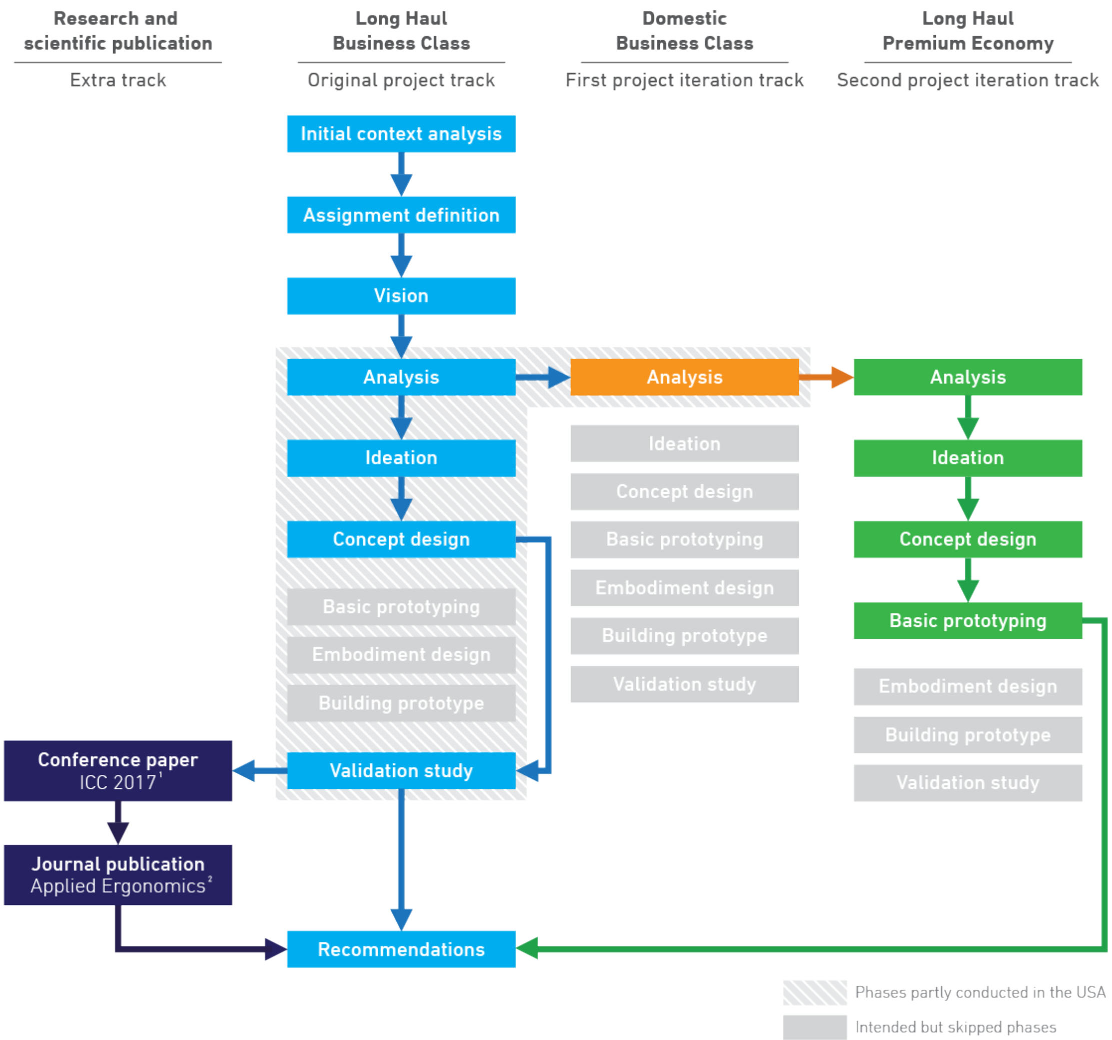


Figure E.1 | Schematic representation of the project process

[1] Conference paper presentation at the International Comfort Congress 2017, Salerno, Italy
[2] Paper submitted at Applied Ergonomics for special issue on comfort.

Reading guide

This thesis is structured as chronologically as possible based on project phases and divided into two tracks; *Business Class* and *Premium Economy Class*, focussing on two main topics; facilitating *watching IFE* and *sleeping* in these two cabin classes (see Table R.1).

Table R.1 | Thesis structure

<table>
<tr><th rowspan="2">Project phase</th><th colspan="2">Long haul premium cabin headrest</th></tr>
<tr><th>Business Class</th><th>Premium Economy</th></tr>
<tr><td rowspan="3">Analysis</td><td colspan="2">Context</td></tr>
<tr><td colspan="2">IFE</td></tr>
<tr><td colspan="2">Sleep</td></tr>
<tr><td>Program of requirements</td><td>PoR</td><td>PoR</td></tr>
<tr><td rowspan="2">Ideation and conceptualisation</td><td colspan="2">IFE</td></tr>
<tr><td colspan="2">Sleep</td></tr>
<tr><td rowspan="2">Recommendations for further development</td><td colspan="2">IFE</td></tr>
<tr><td colspan="2">Sleep</td></tr>
<tr><td>Research publication</td><td>IFE</td><td></td></tr>
</table>

Each chapter starts with an *introduction* of the chapter, explaining the contents and relevance to headrest and seat design, and is concluded with a *conclusion* covering the main insights and stating how these affect headrest and seat design. Demands based on the analysis are added to the programme of requirements that can be found in §7.3. Where appropriate a *recommendations for seat manufacturers* section is included, summarising all relevant insights and considerations in (bed) seat design.

Chapter contents

The chapters in this thesis elaborate on the following:

Chapter 1 *Preface* discusses how the project came to be and how it has changed over time.

Chapter 2 *Context introduction* discusses the relevance of this graduation project. It elaborates on the competitive environment of aviation, the relevance of comfort in seating for differentiation and to gain the favour of the well paying premium cabin passengers and explains the focus of this project on sleep and IFE.

Chapter 3 *Assignment deconstruction* states the main challenges in premium economy and business class, defines the scope of this project, explains the taken approach and the added value of this graduation project.

Chapter 4 *Context analysis* introduces – for those less familiar with the context of aviation – the aircraft cabin and the aircraft seating market. It continues with an analysis of the product stakeholders, the state of the art of headrests and gives recommendations on head-headrest contact (pressure and profile). It concludes with explaining the importance of posture allowance and thus the focus of facilitating sleeping and watching IFE within the aircraft seat.

Chapter 5 *Sleeping comfort in transit* explores sleep and the context factors influencing sleep, such as rhythm, temperature, stimuli and posture. These factors pose both challenges and opportunities that can be used or should be taken into account in a new headrest and seat design.

Chapter 6 *IFE comfort in transit* discusses the relation between head, trunk and eye angles and the position and orientation of the IFE screen to come with appropriate recommendations for improving watching IFE in the premium cabin. It includes an AnyBody™, 'expected comfort' and EMG study, which has been published in Applied Ergonomics (see Appendix C).

Chapter 7 *Design vision, challenges and requirements* discusses the formed design vision, found challenges and determined requirements. These give direct in the ideation and conceptualisation phase.

Chapter 8 *Concept design* explores different possibilities in premium economy and business class to improve sleep and IFE comfort in transit through a selection of most promising concepts and ideas. A selection of these is further explored trough paper prototyping and CAD simulations.

Chapter 9 *Evaluation and conclusion* contains an evaluation of the process, concludes this thesis and gives recommendations for further research and development.

Appendix A features the WORK journal publication *Comfort and pressure distribution in a human contour shaped aircraft seat (developed with 3D scans of the human body)* that preceded and lead to this graduation project. It explores the possibility of improving comfort by designing a business class seat based on the human contour.

Appendix B features the ICC2017 conference paper *Neck posture and muscle activity with and without head support in a reclined sitting posture when watching IFE*, which was presented at the 1st International Comfort Congress. It explores the benefit of head support when watching IFE in a slouched posture to the musculoskeletal system and comfort experience.

Appendix C features the Applied Ergonomics journal publication *Neck posture and muscle activity in a reclined business class aircraft seat watching IFE with and without head support*, which is the end result of this graduation thesis. It shows that head support when watching IFE results in a higher expected comfort than without. Although an AnyBody™ simulation showed less muscle tension could be expected, no proof was found in real life EMG measurements.

Abbreviations and jargon

As this thesis contains many aviation and medical abbreviations and jargon, the reader is advised to consult the Glossary on page 124 when unfamiliar with the used terminology. The glossary is divided in three sections. Abbreviations and jargon contains an alphabetical list of all abbreviations and jargon, which sometimes refers to the other sections for a visual explanation. Anatomical position and orientation alphabetical list and visualises the way of describing the position, orientation and movement of parts of the body. The Musculoskeletal anatomy section visualises muscles and bones of the head, neck, eyes and cervical spine.

Measurements

Most aviation related measurements (e.g. seat pitch and width) are given in Imperial units, as this is common in aviation. All other given measurements are SI (*Système international*) units, unless otherwise specified.

Frequent used abbreviations and jargon

See chapter 12 for the full Glossary on Abbreviations and jargon*,* Anatomical position and orientation and Musculoskeletal anatomy, of which the last covers *neck muscles anatomy, eye muscles anatomy and Skull* and *cervical vertebrae anatomy*. Below frequent used abbreviations and jargon are explained:

BC (*BiC*)	Business Class
BCP	Business Class Passenger
Carrier	Commonly used as a synonym of airline.
EC	Economy Class
ECP	Economy Class Passenger
Extension	A straightening movement that increases the angle between a segment and its proximal segment. E.g. bending the head backwards to the back.
FA	Flight attendant
FC	First Class
Flexion	A bending movement that decreases the angle between a segment and its proximal segment. E.g. bending the head forward to the chest.
IFE	In Fligth Entertainment, the screens on board of an aircraft to entertain passengers, featuring (depending on what the airline offers) movies, (live) TV, games, interactive maps, magazines, etc.. These screens are mainly mounted at the upper part of the backrest and for bulkhead seats mounted on an arm, which can be stowed in the armrest.
PAX	Passenger Seat Place, which stands for one passenger seat or one individual passenger, depending on the context.
PEC	Premium Economy Class
PECP	Premium Economy Class Passenger

Table of content

Chapter 1 **Page**

1 Preface

This graduation thesis explores the possibilities for improving comfort and cabin experience for watching in flight entertainment (IFE) and sleeping in business class (BC) and premium economy class (PEC) in the aircraft by a new headrest design. However, this was not the initial assignment. This chapter explains how this graduation assignment came to be, how the focus forcefully shifted, plans needed to be adjusted and finally on how the project had to be redefined.

1.1 Summary

This graduation started as a continuation of an AED project on a human contoured business class aircraft seat for Zodiac Seats US (ZSUS). Dr. Udo Schültheis – director of the Human Factors and Ergonomics department at ZSUS – offered the opportunity to continue elaborating on the headrest design from this project, implementing it in the new long-haul business class bed, which was under development at ZSUS. The aim was to focus on facilitating watching in flight entertainment (IFE) and sleeping. Due to discontinuation of this project at ZSUS without informing me, my assignment forcefully changed into designing a headrest for domestic business class when I arrived at the company location in the USA. Due to unforeseen circumstances at ZSUS and therefrom-arising consequences for the *Human Factors and Ergonomics lab*, we had to stop our co-operation after my time with them in Texas. It was therefore decided to limit and wrap up the co-operation with ZSUS by a scientific research paper. Back in the Netherlands the project changed into designing a headrest to facilitate watching IFE and sleeping in both *premium economy* and *business class*, as research insights and new concept ideas would fit both premium cabins.

1.2 How the assignment came to be

During my masters in Integrated Product Design, Industrial Design Engineering at the Delft University of Technology (TU Delft), I was involved in multiple aviation, comfort and seating related projects, starting with designing guard shelters at the course Advanced Concept Design (ACD) for Amsterdam Airport Schiphol Access Control & Public Security, followed by an Advanced Embodiment Design (AED) project on designing a business class seat based on the human contour for Zodiac Seats US (ZSUS) (see Figure 1.1). This was continued by a research project on that same seat design, studying its comfort by comparing it with a traditional seat. This study has been published in a special issue of the journal WORK in 2016 (see Appendix A). Next was a Joint Master Project (JMP) for office and home furniture manufacturer Gispen on improving productivity in the office, by facilitating dedicated interactions to improve collaboration among office workers. Then I got back into aviation with an internship at the Research and Technology (R&T) teams of Zodiac Galleys Europe (ZGEU) and Zodiac Aircatering Equipment Europe (ZAEE), where I did a research and design project on retaining of containers and trolleys, to improve the process, user-friendliness and safety within the galley. This project resulted in new insights (see Figure 1.2) and two (pending) patent applications for the company.

My interest in usability, efficiency, comfort and user-centred design has grown in these projects, and I want to continue learning on these matters by research and design. When Dr. Udo Schultheis of ZSUS visited our faculty in September 2015 on invitation of Prof. Vink, he showed interest in the initial AED design for a headrest by Ir. Karlien Berghman and me. Dr. Schultheis then proposed to design a headrest with a focus on watching IFE (in flight entertainment) and sleep for a new to be developed bed, which can transform into a seat. This is driven by the increased expectation of a flat bed experiences by business class travellers, so they can land fresh and rested after a long haul flight. Schültheis suggested business class passengers prefer sleeping over sitting during long haul flights (U. Schültheis, personal communication, September 28, 2015). Zodiac Seats US LLC (ZSUS) therefore wanted to initiate a new generation business class seat, which is a bed that can translate to a seat rather than the other way around.

The assignment provoked my interest, as it also offered me the opportunity to work at the Human Factors and Ergonomics department at the ZSUS plant in Gainesville Texas, cooperate with and learn from the team and be guided by Dr. Schültheis – an experienced PhD in human factors and psychology – weekly. In the following months I assembled my supervisory team with Prof. Peter Vink and Elmer van Grondelle, drafted the assignment, prepared my J-1 Visa for the USA, started initial analysis (e.g. see Appendix G) and prepared for the journey.

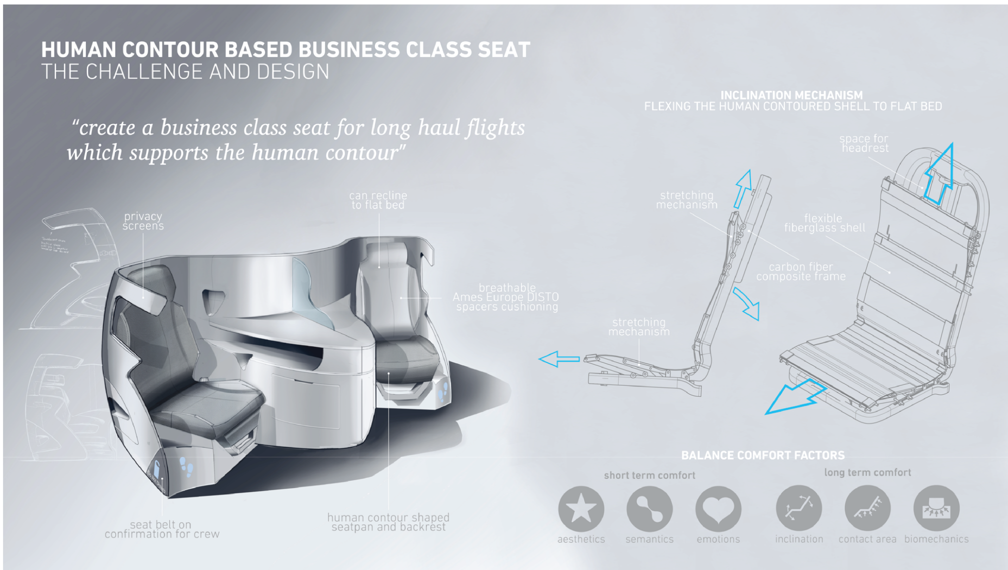


Figure 1.1 | Business class seat based on the human contour AED project for ZSUS

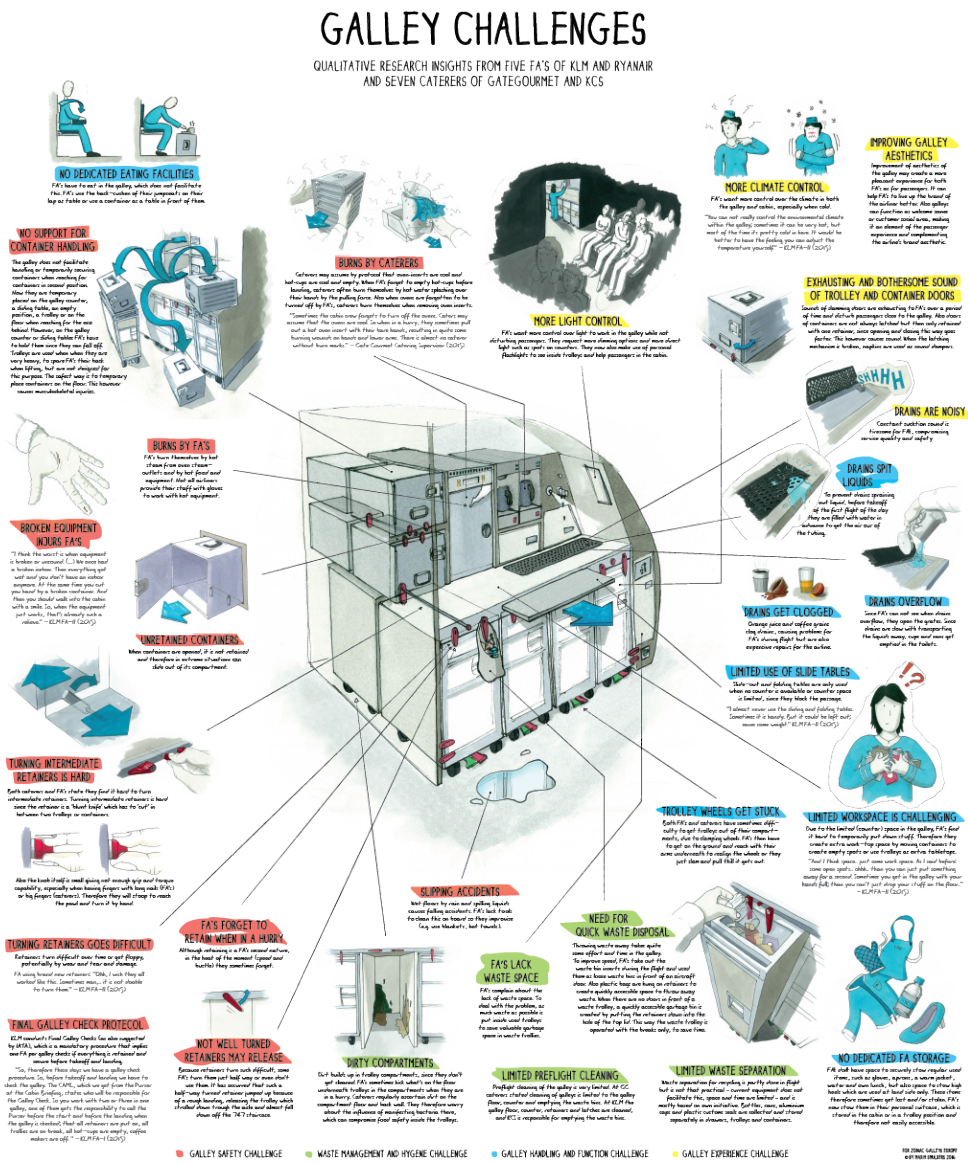


Figure 1.2 | Analysis poster stating challenges, issues and problems in aircraft galleys for ZGEU

1.3 A change of plans: partial co-operation with ZSUS

When I arrived in the USA to live there for five months, not only my environment changed, I also had to adapt to unforeseen challenges and had to change my plans. The original assignment was to contribute to a new to be developed bed-seat (a long-haul full-flat business class seat) by designing a headrest, which supports comfortably and ergonomically the human head to watch in flight entertainment (IFE) and to sleep while the seat is reclined and to sleep while the seat is a flat-bed. When I arrived in Texas, I was told the original project was moved from ZSUS to Zodiac Seast France (ZSFR). Dr. Schultheis suggested to change the project into redesigning the headrest of the Z600, a domestic (short to medium-haul) business class seat, still with a focus on improving comfort by facilitating a better experience in sleep and watching IFE. The seat especially had challenges concerning IFE, the size and weight of the headrest and seat recline (see Appendix F).

The intention was to closely co-operate with Dr. Udo Schultheis and his team in doing research, design, engineering and prototyping. However, due to unforeseen circumstances at ZSUS and the therefrom-arising consequences for the *Human Factors and Ergonomics lab*, we had to stop our co-operation after my time with them in Texas. It was therefore decided to limit the co-operation to the analysis phase and wrap up the co-operation with ZSUS with the presentation of a paper on *Neck posture and muscle activity with and without head support in a reclined sitting posture when watching IFE* (see Appendix B) at the *International Comfort Conference* in Salerno, Italy. This research paper was further elaborated on in co-operation with Prof. Alessandro Naddeo and Prof. Nicola Cappetti of the University of Salerno, Italy, and has been accepted for publication in a special issue of *Applied Ergonomics* on comfort (see Appendix C).

Original long haul business class seat assignment:

"Develop a headrest based on scientific research (e.g. interviews, biomechanical analysis, user testing, researching behaviour while sleeping & watching IFE), which supports comfortably and ergonomically the human head to watch IFE while the seat is inclined and sleep while the seat is a flat-bed. The design should fit the new flat-bed seat design, which is currently in development by Zodiac Seats US LLC (which is a bed which can become a seat, instead of the other way around). The assignment will be focused on the headrest, but it should consider the entire seat since the headrest is an integral part of the whole seat and the travel experience."

Secondary Z600 assignment:

"Develop a headrest based on scientific research (e.g. interviews, biomechanical analysis, user testing, researching behaviour while sleeping & watching IFE), which supports comfortably and ergonomically the human head to watch IFE and sleep while the seat is reclined. The design should fit the Z600 seat design, which is currently in redevelopment by Zodiac Seats US LLC. The assignment will be focused on the headrest, but it should consider the entire seat since the headrest is an integral part of the whole seat and the travel experience."

1.4 Redefining the project

Already in the USA I felt conflicted about the Z600 project, as the focus on sleep and IFE of the product did not meet the context of a domestic flight. In this context sleeping (napping at most) makes no sense, as domestic flights are mostly short- to medium-haul day flights. This is also often too short for watching a full movie (averaging between 1,5-3h in length) and airliners often consider IFE as too expensive, space consuming and heavy for short- and medium-haul flights.

When back in the Netherlands the supervisory team and I redefined the assignment from domestic (short-haul) business class back to the original context of long-haul business class (BC) with the addition of long-haul premium economy class (PEC), focussing on improving sleep and IFE comfort and experience (see chapter 3). It was decided to focus on premium cabins, since there is more room for investment by airlines and product differentiation in these cabins is key due to high competition among airliners and the need for justification of higher ticket prices (see chapter 2). Also analysis and research insights and new design ideas fitted both classes – each with its own challenges – well.

Final redefined assignment on BC and PEC:

"Develop a headrest based on scientific research (e.g. interviews, biomechanical analysis, user testing, researching behaviour while sleeping & watching IFE) for a long-haul business class and premium economy class seat, which supports comfortably and ergonomically the human head to watch IFE and sleep.

The assignment will be focused on the headrest, but it should consider the entire seat since the headrest is an integral part of the whole seat and the travel experience. Secondary, it is important that the seat facilitates a multitude of activities too – such as the TTL position as is mandatory by regulations – to not restrict the passenger."

Although it was the intention to further elaborate on the concept designs through paper prototyping, embodiment design, prototyping and testing, due to external factors beyond our influence this was not possible. The supervisory team therefore decides to have the scientific journal publication as the final product of this graduation project (see Appendix C). Based on this paper, other research and concept designs, this thesis also concludes with recommendations for further development of both a full BC seat design and a PEC headrest for a better sleep and IFE experience.

Figure 1.3 shows a schematic representation of the project process, going through the original and adjusted assignments. Arrows show the continuation through the project stages and the flow of information. Stages in grey were planned, but had to be skipped due to circumstances out of my control and time constraints.

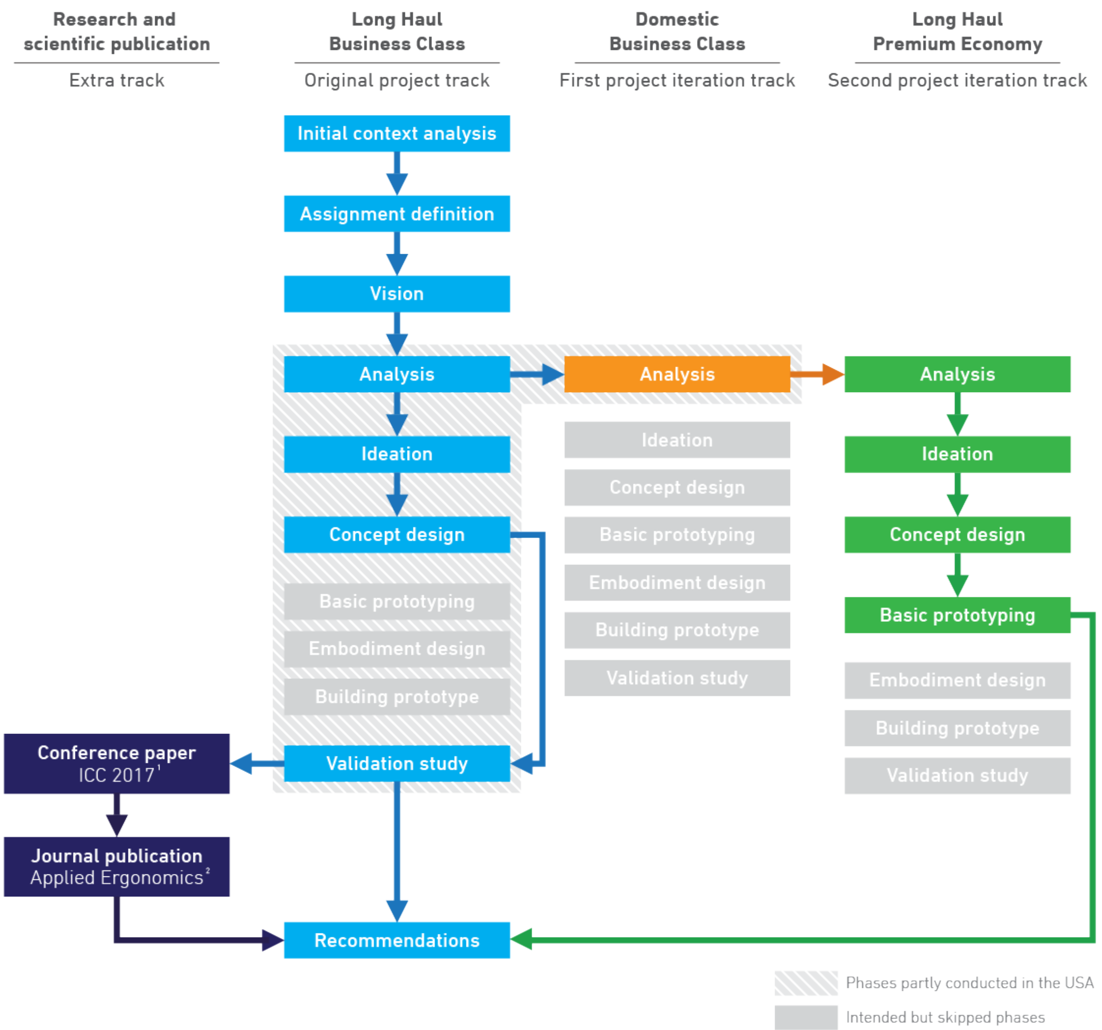


Figure 1.3 | Schematic representation of the project process

[1] Conference paper presentation at the International Comfort Congress 2017, Salerno, Italy
[2] Paper submitted at Applied Ergonomics for special issue on comfort.

Chapter 2 **Page**

2 Context introduction

This chapter is setting the scene by showing the context of this graduation project; the competitive world of aviation. It elaborates first on the challenges of seat design – balancing the different interests of the different stakeholders – followed by an explanation of the importance of comfort for airline product differentiation. Next it discusses the classification of aviation and the economics behind it, explaining the importance of premium cabins to airlines. It further discusses Business Class and Premium Economy Class. And lastly the main activities on board the aircraft IFE and sleep, and the importance of control are discussed. Based on this context the assignment is formulated, as will be discussed in the next chapter.

2.1 Summary

Seat design is all about balancing conflict of interests. To airliners PAX per ft^2, seat weight (directly related to fuel consumption) and differentiation (a.k.a. margin maximisation) are most important, where passengers want the most comfortable flight experience for the best price. The challenge is for the designers and engineers to meet the wishes of both, while always making sure the final product is economical.

Aviation is a very competitive market. One way for airlines to differentiate themselves – besides ticket price – is by service and comfort experience (Brauer, 2004). For the upcoming 10-20 years innovation will more likely take place on aircraft interiors, as major aircraft manufacturers such as Airbus and Boeing will not introduce any new models soon (T. Clark, 2016). Especially the seat here plays a fundamental role, since it is the longest contact point of the passenger during flight and (premium) passengers are expecting more and more comfort (Vink & Brauer, 2011).

Airliners make the most revenue in premium cabins (Mouawad, 2013; Rosenbaum-Elliott, Percy, & Pervan, 2015). Besides the phasing out first class, one can see two important trends in the premium cabin: first, there is a big warfare for the favour of the well-paying and frequent flying BCP by implementing (first class) perks with a focus on full flat sleeping and a better flight experience (e.g. through IFE, superior meals and services). Secondly, the implementation of the new and most revenue per ft^2 generating premium economy, seducing economy class passengers to upgrade for more comfort and at the same time offering a comfortable alternative for business class passengers who are not allowed to fly in the expensive business class cabin anymore due to changes in company policies (as a consequence of the recession).

The high competition, in combination with the need for justification of the high ticket prices in premium cabins and the increase in expectations of (premium) passengers, forces airliners and their (seat) suppliers to constantly innovate and invest in superior comfort and experience features, such as a better sleep and IFE experience. Especially, since frequent business class passengers find sleep and IFE most important (Vink, Vledder, Smulders, Bronkhorst, & Hiemstra-van Mastrigt, 2017). Airliners therefore start increasing the rate of upgrading or overhauling their cabins (Garcia, 2014a) to keep them more up to date with the wishes and expectations of passengers.

This calls for innovation and the willingness of airlines to invest makes it an interesting time for cabin interior designers, engineers and seating companies, to improve flight comfort and experience in order to help airliners to differentiate themselves, while continuing flying current aircrafts.

2.2 The challenge of aircraft seat design; balancing conflict of interests

When travelling by train or boat, a passenger has the luxury of space; one can get up and walk around. On a bus or car passengers have a more limited space, but can make a regular stop to stretch their legs. In contrast an aircraft passenger is locked up in a pressurised tube 35,000 feet (~11 Km) in the air, travelling 475-500 knots (878–926 km/h) in limited space, making them spend almost the entire duration of a trip in their seat. From this perspective, seat quality and cabin experience are essential comfort factors to the passenger. However, the passenger's desire for adequate living space stands in opposition to the financial necessity of airlines to fit as many passengers (PAX) as possible into an aircraft for revenue maximisation. To compensate for the limited amount of living space in the cabin, aircraft seats offer adjustability to facilitate multiple postures and activities, such as backrest recline and a tray table. To minimise operating costs, airliners also aim for light aircrafts to save on fuel and therefore aircraft seat manufacturers are constantly pushed to make their seats lighter (Eisenbrand, 2004; Schultheis, 2016a).

To make things even more challenging, aircraft seats have to meet strict safety requirements, such as materials must meet though flammability regulations and the construction needs to withstand stresses of up to 16G in crash tests. Seats should also offer a comfortable flight as long as over 12 hours for passengers with all kinds of different anthropometrics, such as length (tall vs small) and posture (fat vs slim). And lastly, an aircraft seat has to endure prolonged and intensive (miss) use and vandalism by passengers for at least ten years (Eisenbrand, 2004; Garcia & Skift, 2014; Le, 2015; Schultheis, 2016a; Snider, 2016).

The conflict of interest between the comfort requirements of passengers, the commercial driven spatial constraints, weight and durability requirements of airliners and governmental safety requirements are a fundamental condition of aircraft seat design and production (see Figure 2.1). This makes aircraft seat design and manufacturing such complex and challenging. Therefore aircraft seat design has become a specialised, engineering driven industry (Eisenbrand, 2004; Snider, 2016).

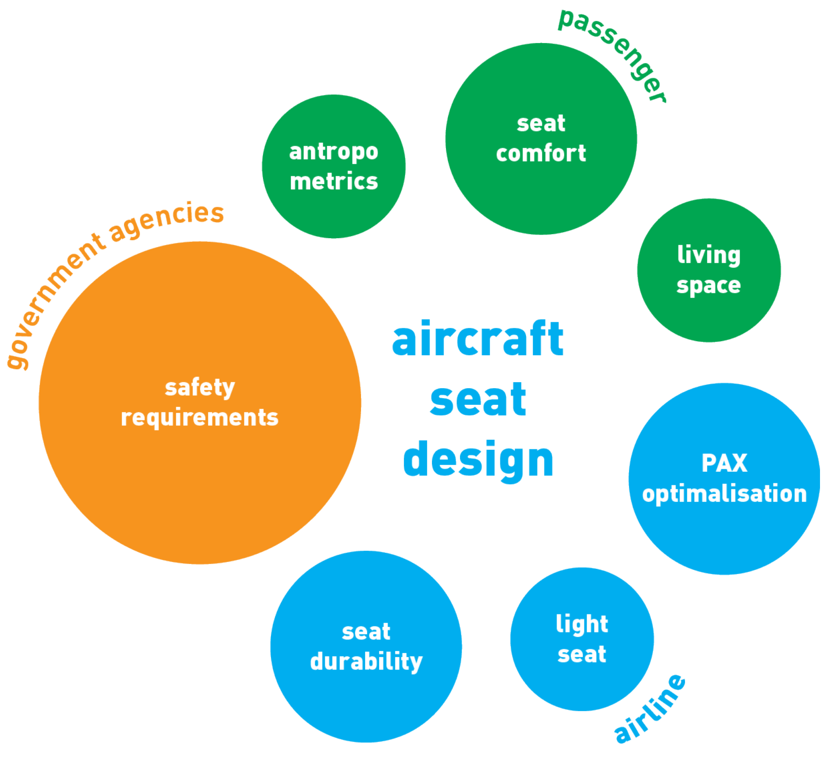


Figure 2.1 | Interests of the main stakeholders

2.3 Comfort: the weapon in the battle for PAX and market share in premium cabins

Aviation is a very competitive market. Especially after the deregulation by the International Air Transport Association (IATA) in the 50's, airliners started to compete for market share. Nowadays, established airliners struggle due to high oil prices, but also due to heavy competition of newcomers, the introduction of new business models, technological innovations such as the Internet (and the ease of comparing prices) and the merge of legacy carriers into new big airline corporations.

One way for airlines to differentiate themselves from their competition – besides ticket price – is by service and comfort experience (Vink & van Mastrigt, 2011). Brauer (2004) (former director of Passenger Satisfaction and Revenue at Boeing Commercial Airplanes) argues 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. Here comfort and service have a higher priority on long haul flights (Brauer, 2004; Vink & Brauer, 2011). As stated by Bob Lange (senior vice president of market and product strategy at Airbus), passengers still pick airlines based on the availability of flights and schedule, but that now the 'cabin product' (which has big influence on the flight experience and comfort) is right behind that (Mouawad, 2013).

This can be found back in a study of Alamdari (1999) (n=100) where business class passengers (BCP's) stated the influential factors affecting their choice for a flight were, in order of importance: reliability, punctuality, schedule, seating comfort, flight crew, image of the airliner and price (see Figure 2.2). Similar results were found in the study by Bieger, Wittmer, and Laesser (2007) (n=1000), where BCP's stated the importance of different buying criteria for intercontinental direct flight connections (in decreasing order of importance): direct connection, safety, total travel time, punctuality, travel comfort, time departure and arrival, sympathy/brand (loyalty), total travel costs, mileage program, status and lastly number of daily connections (see Figure 2.3). In general, price can be considered less important by BCP's, since the organisation they work and fly for pays for the travel expenses. Comfort is therefore considered a more decisive factor. However, when looking at the hidden-preference of BC and EC passengers, price dominates, followed by number of stops, the airline and lastly the number of daily connections (Bieger et al., 2007). This was true for both BC as for EC passengers.

What is interesting from Alamdari (1999)'s study is that BCP's find seating comfort less important than economy passengers (see Figure 2.2). In the study of Blok, Vink, and Kamp (2007) BCP's and ECP's do not rate comfort significant differently. This can be explained by the significant difference in seating comfort between the classes and the class depended expectation.

BCP's know what to expect and therefore may rate seating comfort as less important. Due to the lack of space and minimal comfort in EC, ECP's are more conscious about the importance of their seat choice (since cabin and seats may differ among carriers and aircraft), where BCP's expect a certain level of comfort in BC. That however, does not mean they do not care about comfort. In the study with Vink et al. (2017) BCP's clearly stated they consciously chose to fly BC for its comfort. Vink and Brauer (2011) state that airline passengers expect greater comfort in PEC or BC than in EC.

It can be concluded that premium cabin passengers consciously consider the comfort aspects when booking their premium class flight and are willing to pay extra for the extra comfort (Balcombe, Fraser, & Harris, 2009; Kuo & Jou, 2017). Seats play fundamental role in this comfort, as they are the longest contact point of the passenger during flight. As premium cabin passengers are expecting more and more comfort (Vink & Brauer, 2011), innovation is important here.

2.4 Innovation and differentiation has to come from the inside

As stated by T. Clark (2016) and Hiller (2016) for the upcoming 10-20 years innovation will more likely take place on aircraft interiors, as major aircraft manufacturers such as Airbus and Boeing will not introduce any new models anytime soon. The cycle time for big redesigns used to be 10 years, but since the big manufacturers focus on incremental improvements such as fuel efficiency of their current models and airliners are refitting and upgrading their old aircraft to expand their life span, the current cycle time for big redesign of aircraft are estimated close to 20 years (Shankland, 2014).

At the same time airliners are shortening the life cycles of their interior programs, updating and/or replacing them sooner than before due to rising passenger expectations (driven by high phases innovation in consumer electronics) and increased competition (Garcia, 2014a). Hence, this is an interesting time for cabin interior designers, engineers and companies, to improve flight comfort and experience in order to help airliners to differentiate themselves, while continuing flying current aircrafts (Clayton & Hilz, 2015; Hiller, 2016; Vink, 2015).

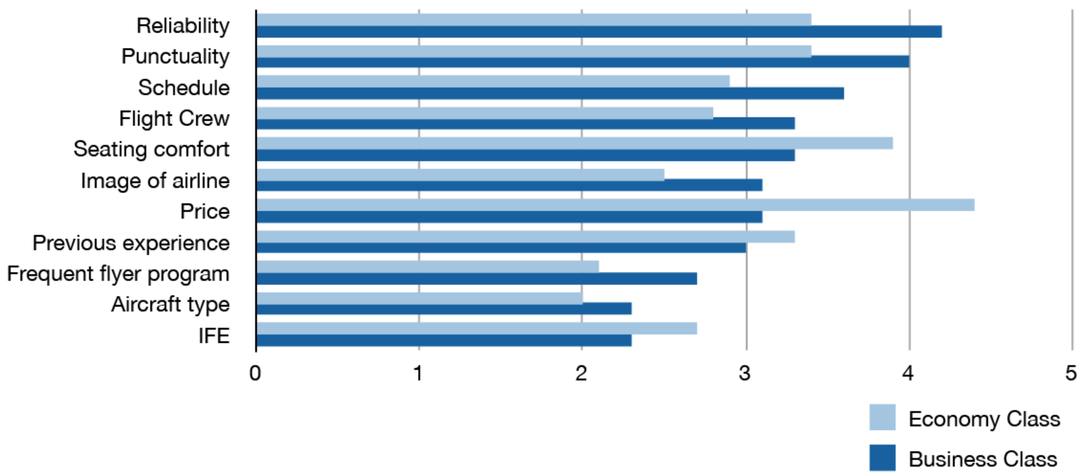


Figure 2.2 | Factors influencing passenger choice of airline (n=100, from Alamdari (1999))

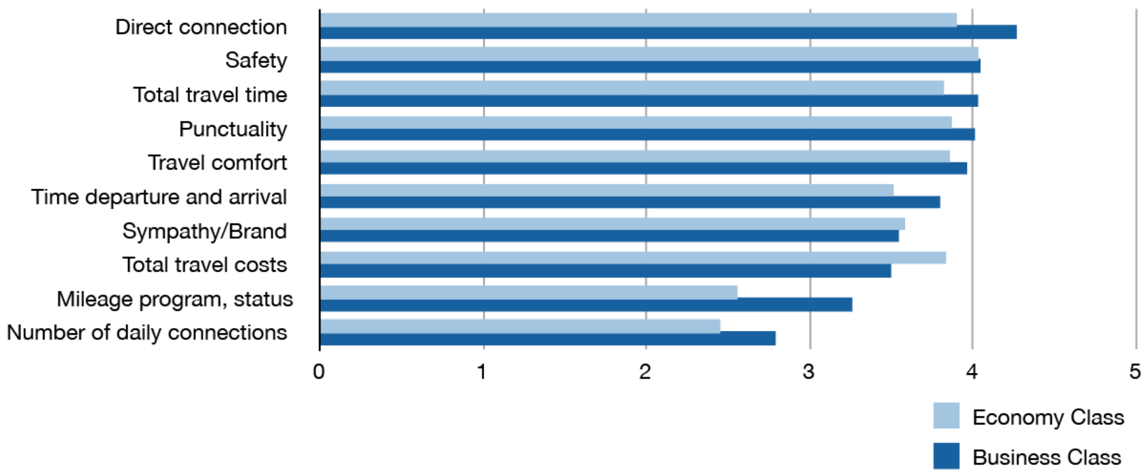


Figure 2.3 | Factors influencing passenger choice of airline (n=1000, based on data of Bieger et al. (2007))

2.5 The importance of premium cabins to airliners

"The business and corporate travel market is by far the most lucrative one for the airlines. (...) Carriers are vying for the attention of these passengers, who have money or corporate accounts that pay for their travel, are counting on good design to escape the grinding commodity nature of their business."

Samuel Engel, vice president at ICF SH&E (an aviation consulting firm)

"Business class is where competition really is serious"

Björn Bosler, manager passenger experience design, Business and premium, Lufthansa

Premium cabins are important to airliners for multiple reasons. The first is revenue and profit margins. First and business class may just represents 10-15% of the long-haul seats globally, but is accounts for up to 50% of the revenue of major airliners such as Lufthansa or British Airways (Mouawad, 2013; Rosenbaum-Elliott et al., 2015). The second reasons for airliners why premium cabins are of such importance is income stability. Where economy is very season dependent (holidays, vacations, weekends), business travel is more stable (Derudder, Beaverstock, Faulconbridge, Storme, & Witlox, 2011) and thus a more reliable source of income.

Although *business* makes the most revenue (see Table 2.2), there is no sufficient demand to fill entire planes with *business* only (although there were airliners who tried of which many failed (BBC News, 2008; Bland, 2008)). Just like in the 70's, *economy* is still important to 'fill up' the plane to cover operation costs and keep airlines in business. Due to high competition among airlines on price (it is the passenger who makes a choice based on their wallet), *economy* has been stripped down, becoming minimalistic and compact, making it cost-effective to be positioned competitively. The pressure on ticket price also makes the profit margins very low and thus to make decent profit, airliners try to maximise the amount of EC passengers within the limited space as possible. As can be seen in the example in Table 2.1, *economy* makes the least revenue per ft^2. But thanks to its volume, as shown in Table 2.2, it makes up 28% of the revenue per flight.

Despite its high volume, *economy* is not where airliners make profit; they do that in the premium cabins where the margins are higher (Mouawad, 2013; Rosenbaum-Elliott et al., 2015), especially in *premium economy* (with the highest revenue per ft^2) (Hugon-Duprat & O'Connell, 2015) and *business class* (with the percentage of total revenue). As can be seen in Table 2.2, 47% of the passengers (all in the premium cabin) accounts for 72% of the revenue. Thus EC is sometimes seen as a way to 'fill up' the airplane to cover operation costs.

Despite that, it is important to notice that having a decent flight experience in the back of the plane is still important to persuade *economy* passengers to choose for a carrier in the first place, to give the airline exposure, to create certain brand qualities and persuade passengers to be loyal to the airliner. This can stimulate passengers to eventually upgrade themselves to premium cabins, like *premium economy* and *business class*.

Table 2.1 | Revenue per ft² on a British Airways Boeing 747-400 (V3) flying daily between London Heathrow and JFK New York. Prices are for a June 12-June 19 return flight as stated on May 2nd, 2017. Currency correction on May 2nd, 2017. (British Airways, 2017; Garcia, 2016; Seat Guru, 2016)

Class	Ticket	Seat space	Revenue per ft² (per m²)
Economy	€ 605,32	3.77ft2 (0,35m2)	€ 160,56/ft2 (€ 1.729,48/m2)
Premium Economy	€ 1.092,90	4.88ft2 (0,45m2)	€ 233,96/ft2 (€ 2.428,67/m2)
Business	€ 1.861,14	10.14ft2 (0,94m2)	€ 183,54/ft2 (€ 1.979,94/m2)
First	€ 2.378,46	12.07ft2 (1,12 m2)	€ 197,06/ft2 (€ 2.123,63/m2)

Table 2.2 | A British Airways Boeing 747-400 (V3) flying daily between London Heathrow and JFK New York. Prices are for a June 12-June 19 return flight as stated on May 2nd, 2017. Currency correction on May 2nd, 2017. (British Airways, 2017; Garcia, 2016; Seat Guru, 2016). Prices and proportions among classes were roughly the same at Lufthansa (FRA-JFK) and KLM (AMS-JFK) for the same dates.

Class	Ticket	Seats	Total revenue (at theoretical 100%)	% total seats	% total revenue
EC	€ 605,32	145	€ 87.771,12	53 %	28 %
PEC	€ 1.092,90	30	€ 32.787,07	11 %	10 %
BC	€ 1.861,14	86	€ 160.058,47	31 %	51 %
FC	€ 2.378,46	14	€ 33.298,44	5 %	11 %

2.6 The battle for the business class travellers' favour

"There's an arms race going on among carriers."

Bob Lange, SVP, market and product strategy, Airbus

2.6.1 Why do we (still) fly business class?

In the late 1970's, the new jumbo jets – like the 747 – were introduced. This meant spacious and comfortable cabins, but not for long. The bigger, faster and therefore more economical aircraft resulted in lower ticket prices, making flying available for the masses. As the years passed, more seats got taken by holiday travellers on discount fares, who enjoyed the same perks, same food, same seats and stood in the same lines as the full fare-paying passengers. Business class travellers perceived this as unfair. 1976 KLM therefore introduced a Full Fare Facilities, which can be seen as the start of Business Class separation from Economy Class. It allowed full fare economy passengers to sit upfront right behind First Class, which was soon copied by other airliners (Danard, 1978). Over the years, this developed into business class we know today (see also §14.7).

These days, one could argue that due to technical advances such as email and video conferencing, business air travel would be less necessary and would be replaced by at least some amount. As investigated by many, this is the case; nevertheless of minor proportions. Denstadli (2004) found a decrease of 7% in USA by 2010, 2.5–3.5% in Norway between 1998 and 2003 and Roy and Filiatrault (1998) found 1.8% in Canada in the long-term. Despite all the technological advances, it still cannot replace the quality of face-to-face meetings.

A study by Lu and Peeta (2009) suggests that "the meeting context is a key factor that influences the choice of business air travel and videoconferencing. Business air travel is induced by meetings that require face-to-face communication such as business discussions, negotiations, marketing demonstrations, and event participation, while videoconferencing is adequate for information exchange, management meetings, training, and consulting." Several studies of communication and business travel have confirmed that regular face-to-face interaction is required to ensure development of trust, reciprocity and mutual understanding (Nardi and Whittaker (2002); Storper and Venables (2004); Nohria and Eccles (1992); Kiesler and Cummings (2002); Jones (2007); Weterings and Boschma (2009)).

This is why business travel still remains relevant. And to remain productive, business class travellers need to fly relatively comfortably over long distances to remain productive (Mouawad, 2013). To do so, a good rest and sleeping experience is key.

2.6.2 The new weapon: the full flat-bed seat

"The one thing business fliers really care about is sleep."

Uta Kötting, Lufthansa design team

"Many business-class cabins are now as comfortable – or even more so – than the first-class cabins of five or ten years ago"

Jennifer Coutts Clay, seat expert and head of J. Clay Consulting (Peterson, 2012)

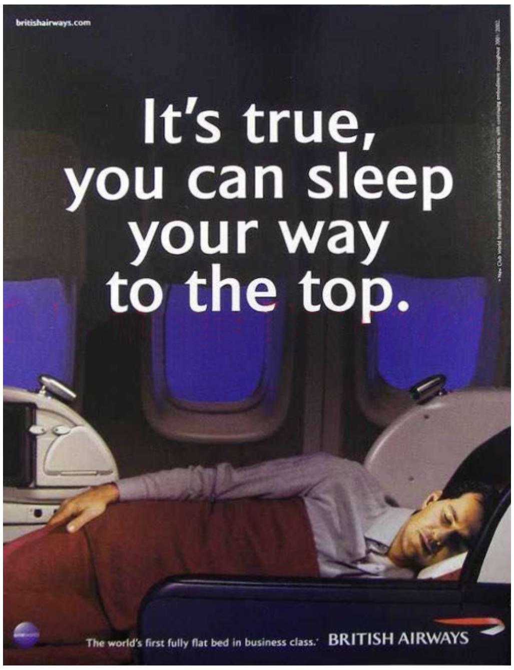


Figure 2.4 | 2001 British Airways Business Class advertisement 'Sleep your way to the top'

As stated before, the first airplane business-class sections date back to the 1970s. Those seats were like oversized padded armchairs that could recline about 40 degrees. More comfortable seats for frequent business travellers came with the arrival of long range aircrafts in the 1990's – like the Boeing 777 – which could fly long distances nonstop. Those long haul flights of 10 to 14 hours meant that passengers wanted do be able to get some real sleep on board, "not just a fitful, head-snapping catnap" (Mouawad, 2013). Thus were cradle-style and angled-flat seat introduced, which were comfortable, but did not offer the qualitative good night sleep of a full flat seat. Passengers who wanted such a full flat seat, often had only one option: an expensive ticket for international first class (Sumers, 2017).

The battle for the favour of the well paying business class traveller reached new heights in 1999, when British Airways introduced the first full flat bed seat (see Figure 2.4) for their Club World business class passengers (British Airways, 2016; J. Clark, 2014; Peterson, 2012; Rosenbaum-Elliott et al., 2015). This was seen as a quantum leap in *business class* comfort, with space of which prior was only considered for the super wealthy who could afford *first class* opulence (J. Clark, 2014). This set the bar for other airliners, which had to follow (Kollau, 2012; Rosenbaum-Elliott et al., 2015) with a new generation of business class seats which can recline to a lie-flat- (170°) or flat bed (180°).

2.7 The new bird in the skies: premium economy

In the quest for profit maximisation, Virgin Atlantic introduced in 1992 a class between *economy* and *business class* as the first: *premium economy class* (PEC). It offers more perks than *economy*, such a separate cabin directly behind business, better seating with more legroom and bigger recline and enhanced IFE with bigger screens. Today, some airliners in addition offer supplementary baggage allowance, additional Frequent Flyer points, dedicated check-in counters, priority boarding, laptop power ports, wider variety of meals, dedicated toilets on board, welcome drinks and even amenity kits. It is important to note that PEC at European airliners offer a different seat, often with a bigger recline, where American airliners offer the same seat with just more pitch (Garcia & Skift, 2014).

PEC is meant to seduce passengers who cannot afford the luxury of a *business class* seat (which on average is three times or more than of an *economy* ticket), but are prepared to pay 30-50% extra for the comfort of a more generous seat and quiet cabin (e.g. without children). This is very profitable, since *premium economy* has the same cabin service – and therefore the operation costs – as *economy*; the only difference is in the seat. The seat is wider and the pitch bigger, making them take 29% more space in the cabin (3.77ft^2 vs. 4.88ft^2). The seat is 1,6 times more expensive than a standard EC seat (Hugon-Duprat & O'Connell, 2015). However, the ticket price – based on the example of Table 2.2 – differs by 81% (€605 vs. €1093). This makes premium economy the most profitable per ft^2, especially when one considers that the service and therefore the operation cost for premium economy is mostly the same as economy.

However, there is also a potential harmful side of PEC to airliners, which made them initially reluctant to implement PEC in their cabins. Due to its lower price but better seating than economy, PEC could cannibalise BC. This was especially the case right during the recent recessions and economic crisis's world wide, when business travellers flew less BC. This made airlines expedited the introduction of PEC in their cabin, in order to prevent business travellers to downgrade and to sustain a higher yield. Although the economy is recovering and the proportion of BCP's is growing back again, the travel policy changes at companies still have their impact on BC air travel in general (Hugon-Duprat & O'Connell, 2015).

Despite this, PEC is an interesting substitute to the cabin class mix, offering passenger with different priorities and requirements dedicated products. PEC can also enhance the airline reputation among travellers in standard *economy* and retain a base of loyal customers (Niţă & Scholz, 2011). Nowadays, premium economy targets price sensitive business travellers and comfort seeking leisure passengers (Hugon-Duprat & O'Connell, 2015). Over 27 airlines currently offer PEC on their long haul flights and this amount is still growing.

It is important for airliners to differentiate PEC from EC and justify its costs by offering superior comfort features, such as a better sleep and IFE experience (Hugon-Duprat & O'Connell, 2015; Kuo & Jou, 2017). Offering superior sleeping capabilities in PEC could persuade EC passengers to upgrade and may even increase the demand for PEC seats. Although there will always be place for cheap 'bare fares', EC passengers increasingly will request more and more the comfort of PEC as EC gets stripped down more and more to a minimum.

2.8 On board activities

In designing an aircraft seat, it is important to consider the user activities conducted in those seats, to facilitate a comfortable flight. Studies by Kamp, Kilincsoy, and Vink (2011) (see Table 2.3), Greghi, Rossi, Souza, and Menegon (2012) (see Table 2.5) and IATA (2012, 2013, 2014, 2015, 2016a) (see Table 2.6) on activities in aircrafts and trains imply that resting, sleeping (recovery), reading and watching IFE (entertainment) are among the most conducted activities in transit. Interviews (Berghman et al., 2014) and online commentary (Fickling, 2014) confirm this. In a survey by American Express in 1999 (as quoted by Alamdari (1999)) 54% of the BCP's indicated to relax while flying, where 26% indicate they like to work during flight. In a more recent study by Vink et al. (2017) (see Table 2.8) shows that BCP's mainly watch IFE (34%) and sleep (35%). Those passengers considered sleep and watching IFE also as the most important activities during flight (see Figure 2.5). As a motivation they stated that feeling refreshed and rested when landing was the most important reason to fly BC. Alamdari (1999) gives an order of preference of in flight activities of both economy and business class passengers (n=100): sleep & relax, be entertained, read, work and other.

The hypothesis as to why they score such high is that reading, IFE and sleep distract the passenger of the restrictions and discomfort they undergo and passes time quick. A passenger is locked up in the aircraft high in the sky and has to surrender oneself to the crew. Also the service (regime) is predefined; imposing what passengers can or cannot do at certain moments during flight. Limited in their freedom, movability and choice, passengers probably try to pass the time as quickly as possible by finding distraction or by being unconscious.

Table 2.3 | Most observed activities during the train journey (n=568) (Kamp et al., 2011)

Activities	Percentage of activity observed
Talking/ discussing	23,6%
Relaxing	**23,4%**
Reading	**19,7%**
Sleeping	**13,7%**
Watching (outside)	8,6%
Using small electronical devices	3,9%
Working - Using large electronical devices	3,9%
Eating / Drinking	3,2%

Table 2.4 | Activities performed in the train based on frequencies of n=786 short observations (Groenesteijn et al., 2014)

Activities	% of total activity during train journey (based on frequency)	Average duration in minutes
Reading from paper	26%	28min (1min-1h8min)
Staring or sleeping	**25%**	29min (1min-1h29min)
Working on laptop	**16,9%**	53min (14min-1h52min
Talking	10%	17min (1min-36min)
Using PDA	6,9%	Not investigated
Listening to music	4,4%	Not investigated
Eating/drinking	3,8%	Not investigated
Other	2,9%	Not investigated
Writing	2,3%	Not investigated
Making phone call	0,8%	Not investigated

Table 2.5 | Performed activities in an aircraft by passengers and the experienced difficulty in percentages (n=287) (Greghi et al., 2012)

Activities	% of passengers who perform the activity	% of passengers who find some difficulty in performing the activity
Resting and sleeping	**83,37**	**76,68**
Eating	91,10	46,06
Reading, writing and working	80,58	42,37
Entertainment Activity	**56,16**	**50,00**
Going to the toilet	54,87	40,63

Table 2.6 | Favourite activity during flight (n=unknown) (IATA, 2012, 2013, 2014, 2015, 2016a)[1]

Activities	2012	2013	2014	2015	2016 Long-haul	2016 Short-haul	*Average (excl. 2015-16)*
Watching IFE	**41%**	**38,2%**	**38%**	**72%**	**77%**	42%	*39,1%*
Reading	21%	23,8%	15,8%	n.a.	n.a.	53%	*20,2%*
Sleeping	**17%**	**18,6%**	**17%**	**70%**	**69%**	38%	*17,5%*
Looking out of window	n.a.	n.a.	12,5%	n.a.	n.a.	n.a.	*n.a.*
Eating/drinking	9%	8,9%	7,6%	42%	40%	n.a.	*8,5%*
Browsing the internet	n.a.	n.a.	2,8%	n.a.	n.a.	n.a.	*n.a.*
Working	2,7%	2,3%	2%	n.a.	n.a.	n.a.	*2,3%*
Chatting to others	8%	3,1%	1,6%	n.a.	n.a.	n.a.	*4,2%*
Other	3,7%	3,2%	1,4%	n.a.	n.a.	n.a.	*2,8%*
Playing games	1,2%	2%	0,9%	n.a.	n.a.	n.a.	*1,4%*

[1]Approach, sample size and sample diversity are not published and scientific ground is thereby debatable.

Table 2.7 | Percentage of n=149 aircraft passengers performing the activity (based on Bouwens as cited by Vink (2016))[2]

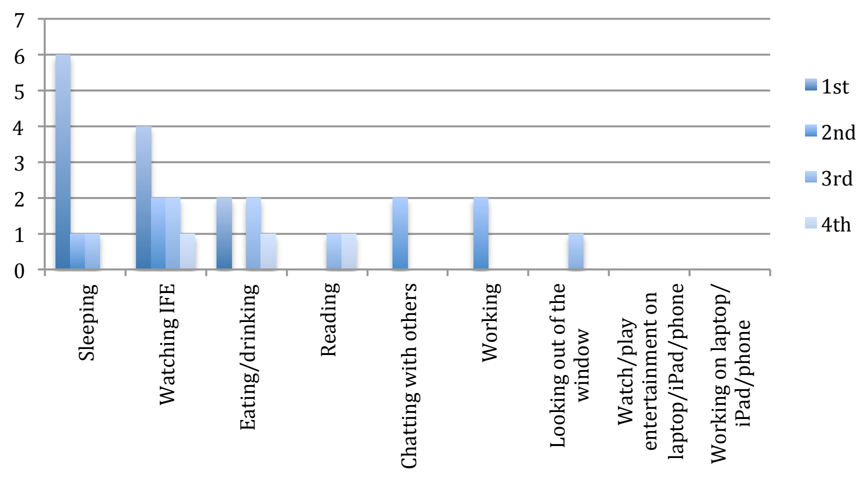
Activity	Percentage
Gaming	23%
Watching IFE	**44%**
Having food	60%
Walking through the plane	61%
Being bored	64%
Reading	68%
Listening to music	73%
Sleeping	**79%**

[2] Approach and conditions unknown

Table 2.8 | Percentage of (self proclaimed) time spend on activity during flight by frequent business class travellers (n=10) (Vink et al., 2017)

Activities	Percentage
Watching IFE	**34%**
Sleeping	**35%**
Eating/drinking	9%
Reading	7%
Chatting with others	5%
Working	5%
Looking out of the window	2%
Watch/play entertainment on laptop/iPad/phone	2%
Working on laptop/iPad/phone	1%

Figure 2.5 | Most important activities (from 1st to 4th) considered by frequent business class travellers (n=10) (Vink et al., 2017)



2.9 The demand for a better sleeping experience

"I don't care if they serve dog food or chateaubriand for dinner,
I want to be able to get to sleep as quickly as possible without disturbance
and wake at the last possible minute."

Regular long-haul traveller David Killingback, managing director Singapore at Bank of America Merrill Lynch

Although airliners are still refitting their interiors, the bar is set and business class travellers increasingly expect a good sleep experiences so they can land fresh and rested after a long haul flight. Schultheis (2015) suggests business class passengers prefer sleeping over sitting during long flights. Sleeping during flights is an effective way of spending the otherwise 'lost' time of travel, as it saves spending time on sleep and recovery on the ground, allowing BCT's to work straight out from the aircraft. A good sleep is therefore of great importance to be sharp and effective when landed. For airlines it becomes more important to improve the sleeping capabilities during flight, as premium class passengers expectations and demands increase. Seat manufacturers such as Zodiac Seats US LLC (ZSUS) therefore wants to facilitate better sleeping comfort in their new generation business class seats.

2.10 IFE: an expected service

In Flight Entertainment (IFE) goes all the way back to the 1920's where the first in-flight movies were shown and later included live singers and musicians too (Braggs, 2017b; Spooner, 1925; White, 2012). The technical development of IFE as we know today started with the test of the first in-seat audio/video on-demand systems using 2.7 inch (69 mm) LCD technology by AirVision (nowadays part of Thales (Garcia, 2014b)) in 1988 on a Northwest Airlines' Boeing 747. In the first years personal IFE was only offered in First and Business class, but this changed in 1992 when Emirates offered it to all passengers, soon be followed by Virgin Atlantic and Singapore Airlines (Alamdari, 1999). Where IFE system technology was at least 5 years behind that of consumer products, this changed in the mid 90's with the introduction of video on demand (VOD), which – at the time – was unique (D. Reed, 2006). Since 2000 IFE development went rapid, with introduction of among others bigger screens, touch screens, WiFi and live TV (satellite TV).

Current IFE systems include screen-based video, audio and communication systems and feature in-seat powering options for e.g. phones, tablets and laptops. What is offered depends on the airline and sometimes even on the type of flight or aircraft. Common products modern IFE systems feature are *Video-on-demand*, live TV, *Airmap Display* (showing flight pattern and current location), *Exterior-view* (outside view through exterior camera's e.g. from the pilot perspective), games, destination, arrival and transfer information, ordering services, shopping catalogues and satellite phone.

Although IFE is not among the primary factors affecting passengers' choice, it contributes greatly to passenger satisfaction with the airline service (Alamdari, 1999; Spafax Consulting, 1998). IFE is nowadays more and more an expected feature for long-haul flights by passengers. On short-haul it is less common.

The choice for a system is often made by the airline buying the seat. Although IFE systems are integrated in seats, they are not made by the seat manufacturers but sourced at original equipment manufacturers (OEM), of which the biggest are Thales and Panasonic. Making IFE systems is highly specialised, as the screens require strict safety and certification requirements. For example, an IFE screens need to implode on impact and fragments may not scatter through the cabin. This is to prevent injuries at a crash landing impact, as the head of a passenger may hit the screen. It also requires extra safety features to prevent overheating and short circuit, which can cause fires. And it also needs to work for a prolonged period of time under extensive (mis)use by passengers. This makes IFE systems both heavy and expensive.

One new trend in IFE is *bring your own device* (BYOD) (Le, 2015), as it gives airliners multiple advantages. One is that IFE systems are expensive due to the high safety requirements and certification, but also keeping up with the latest technologies is hard and expensive. Seats are bought for 10-15 years of service. IFE technology, however, goes out of date rapidly when compared to consumer electronics. Passengers therefore complain, since they are used to the latest consumer electronics, especially when they pay premium prices. Airliners also seek for ways to lower seat weight for fuel (and thus money) saving purposes. By offering passengers pre-flight to load via an App or in-flight stream IFE content to their personal devices, airliners save a lot on weight and investment in IFE systems. BYOD's do not require certification and the consumer has the experience they are used to. Other airlines offer passengers an iPad with pre-loaded content (sometimes for an extra fee), as iPad's are cheaper than IFE systems and are certified by the Federal Aviation Administration (FAA).

The question is how BYOD will influence premium cabins. As savings are more relevant in EC due to competition on price, implementation here is more likely. Premium cabin passengers have premium expectations. They do not want to get bothered by the burden of pre-loading content on their devices or the distribution of tablets (e.g. iPad's); they pay more to have hassle free and relax journey. Premium cabin passengers more likely will expect a more conservative but up to date IFE system with a bigger screen than in EC (to differentiate from EC). This will thus be the starting point for this project.

2.11 Lost control for the passenger

Inside the aircraft the passenger has to give up control over their world (after dealing with the unpleasantness of security checks, crowded areas, delays, etc.), as they lose most of their abilities to exercise their free will. As they are locked up in a pressurised tube at 36,000ft traveling 475–500 knots (878–926 km/h; 546–575 mph) for hours, passengers have to surrender to the rules, processes and restrictions of air travel and the will of the cabin crew. The crew determines when restrooms can be used, when meals and drinks are served and when the cabin lights go out to allow sleeping. And often the cabin crew wants everybody to stay seated the whole flight, which makes controlling the passengers and conducting their services easier, but is bad for the passenger experience.

As Schultheis (2015, 2016b) argues, giving passengers more control would benefit their flight experience. It is an area for improvement, which can help airliners differentiate themselves through service, but also through cabin products that allow more control(Sillers, 2016). Airlines such as Emirates already experiment on their A380 with offering their *first* and *business class* passengers meals by order (no fixed meal times), their personal mini bar within their seats and a dedicated bar to visit and meet crew and passengers, with room to move, drinks and snacks (Neistat, 2016a, 2016b). It can be interesting to explore the possibilities to give BCP's more control during their flight.

2.12 Conclusion

Premium cabins are the places were airliners make their profit. Differentiation is essential for airliners to persuade those well-paying passengers to fly with them and to justify the higher ticket prices with respect to *economy*. Premium cabin passengers make their choice based on comfort, and thus expect greater comfort in PEC or BC opposed to EC. To persuade and hold these important passengers, airliners are more willing to innovate and invest in premium cabin comfort and thus also seat manufacturers (such as ZSUS). There is thus a call for innovation and room for investment in premium cabins.

In the aircraft, sleeping and watching IFE are two of the most conducted activities and are considered as important by premium cabin passengers. For the duration of a long haul flight, passengers want to be distracted (e.g. by IFE) or unconscious (e.g. by sleep) of the restrictions of air travel. As a decent sleep requires approximately 7 hours and one movie often takes between 1,5 and 2 hours, passengers spend a considerable amount of time conducting these activities. Thus facilitating adequate comfort for these activities is important.

Considering sleeping during flight, *Business class* passengers expect a full flat bed experience, were *premium economy* also looks for better sleep comfort than in *economy*; they want the second best, since they cannot afford the full flat luxury. Considering IFE premium cabin passengers expect a dedicated (big) screen with the latest technologies (e.g. touch controls and high definition) and a comfortable and qualitative movie experience.

This graduation project therefore focuses on *premium economy* and *business class*, with the aim of improving sleeping and watching IFE comfort.

2.13 Further reading

For further reading on market analysis and forecasts of the aviation market, Le (2015), Lips (2017) and Garcia and Skift (2014) are recommended. For further reading on classification in aviation (its history, trends and economics), please see Appendix I *The history and economics of classification* for a brief overview.

Chapter 3 **Page**

3 Assignment deconstruction

`Now there is a better understanding of the context, this chapter discusses the main challenges in premium economy and business class, defines the scope of this project, explains the taken approach and the added value of this graduation project.

3.1 Summary

This graduation thesis explores the possibilities for improving comfort and cabin experience for watching IFE and sleeping in a business class (BC) and premium economy class (PEC) seat in the aircraft by a new headrest design. The design vision is to allow and support the postures passengers are used to conduct at home, to make them feel less trapped and limited, and may benefit the passenger physical well being and comfort.

In the case of PEC the headrest will facilitate sleeping with limited backrest recline and a mechanism adjusting the IFE screen orientation when the seat in front reclines, featuring height adjustability. In the case of BC the headrest will be an integrated part of an entire seat concept, which focuses on giving back control to the passenger by allowing them to plan their own activities and services during flight. The seat helps them to fall asleep more easily, remain asleep and get woken up according to their sleeping phase and personal wishes. It can also adjust in firmness per area to support a multitude of different sizes of passengers and meeting cultural preferences.

3.2 Problem definition

The new generation *business class* (BC) seats can fully recline into a flat bed, as *business class passengers* (BCP) more and more expect to have an outstanding sleep experience to land refreshed at their destination. As people differ – having different preferences (e.g. considering pillow preferences), tend to sleep in different postures and cultural differences – facilitating a large global audience is challenging.

The *premium economy passenger* (PECP) also looks for better sleep comfort than in *economy* (EC); they want the second best, since they cannot afford the full flat luxury. However, their seat recline is limited, making sleeping difficult, as people sleep best in a horizontal position. To make things more challenging, in a more upright position the head tends to 'fall', resulting in no qualitative sleep (sufficient deep- and REM-sleep). As premium economy passengers expect more comfort than in economy class, an improved sleep experience would improve the *premium economy class* (PEC) marketing position.

When both premium economy and business class passengers want to recline to relax while watching the IFE, they lack neck support to comfortably watch the IFE for a prolonged period of time. Also the IFE screen is not always comfortably and ergonomically positioned. E.g. passengers of different lengths require different screen heights of IFE positioning. Where the IFE screen in BC seats are fixed to the seat's shell, in PEC it is fixed on the backrest of the seat in front. When a passenger in front reclines its seat, the IFE on that backrest gets lowered and miss aligned for the passenger behind, who needs to adjust their posture in sometimes an uncomfortable manner.

A new headrest design should comfortably and ergonomically support the head while watching IFE (which means the headrest and/or the IFE needs to adapt to the users need) and support comfortable sleeping (e.g. in different postures, difference preferences of sleeping) in flat-bed mode for BC and in a reclined position for PEC.

3.3 Assignment

The goal is to improve the comfort experience of long-haul *business class* passengers (BCP's) and *premium economy class passengers* (PECP's) by designing a headrest (and additional components when needed), which facilitates sleeping and watching IFE comfortably and ergonomically in a full flat business class seat and a premium economy seat (with limited recline).

The assignment will be focused on the headrest, but it should consider the entire seat since the headrest is an integral part of the whole seat and thus the travel experience. Contribution to or design the whole seat or parts of it (e.g. backrest, IFE installation) may be necessary. The focus will lie on IFE and sleeping, but eating, working and TTL (the upright taxi, take-off and landing position, due to safety regulations) need to be considered too, to not restrict the passenger.

Note: The project will take into account the strict requirements arising from the industry's standards regarding aircraft seats, materials restrictions, safety regulations and certification processes. However, this is generally done with common sense during graduation project to not limit creativity. Real certification is done in the engineering phase (after R&D), as is common at Zodiac Aerospace.

3.4 Approach

The intention was to do a research-driven design process, where ideation, conceptualisation and embodiment will go hand-in-hand with testing, prototyping, validating, interviews, literature and other forms of research. As described in §0 and 1.4 the assignment was changed into a two-track project: facilitating sleep and watching IFE in long-haul PEC and BC (see Table 3.1). This meant also the approach of the project had to change shifting the focus on research and to a less extend on design. Due to time and planning constraints it was decided that embodiment and prototyping was outside the scope of this assignment. Based on research and explored designs, the project concludes with recommendations on further research and development.

Table 3.1 | Project process

<table>
<tr><th rowspan="2">Phase</th><th colspan="2">Long haul premium cabins</th></tr>
<tr><th>Business Class</th><th>Premium Economy</th></tr>
<tr><td rowspan="3">Analysis</td><td colspan="2">Context</td></tr>
<tr><td colspan="2">IFE</td></tr>
<tr><td colspan="2">Sleep</td></tr>
<tr><td rowspan="2">Ideation and conceptualisation</td><td colspan="2">IFE</td></tr>
<tr><td colspan="2">Sleep</td></tr>
<tr><td>Embodiment design</td><td rowspan="2">Future recommendation</td><td rowspan="3">Future recommendation</td></tr>
<tr><td>Prototyping and evaluation</td></tr>
<tr><td>Research publication</td><td>IFE</td></tr>
</table>

3.5 Added value of this project

The outcome of this project intents to give new ideas and insights on headrest design, head and neck biomechanics and comfort experience, contributing to society (by increases human comfort during travelling in an aircraft) and science (by adding new knowledge). These recommendations and insights may be used in academic research and the aircraft seating industry, but may also benefit other industries too, such as the automotive and (office)furniture industry. As the development of autonomous driving goes fast, functionality of car seats will change. When reaching level 4-5 autonomous driving, car seats may offer IFE and sleeping capabilities to all passengers too.

A new headrest design (or related products) that improves the comfort experience of sleep and watching IFE in the seat, may help seat manufacturers (such as ZSUS, Recaro and BE Aerospace) to offer added value to airliners and differentiate itself from direct competitors. The product can be offered as a standard feature on seats or an optional feature for airliners to choose from.

For airliners, a better comfort experience for premium class passengers may result in higher satisfaction, willingness to fly again and is a way to differentiate itself from the competition. Business class passengers especially are very important for airliners: they produce constant and high revenue due to relative consistency of travel and full fare tickets. Premium economy becomes more and more important on long haul flights, as they increase revenue. These premium cabins can therefore be considered worth to invest in.

The past ten years, the industry has put focus on comfort and experience of passengers. Premium class travellers these days increasingly expect a good sleep experiences so they can land fresh and rested after a long haul flight. It is therefore of importance to aircraft seat manufacturers to keep improving the comfort of their seats to stay competitive. This project may inspire or result in such new products.

Chapter 4 **Page**

4 Context analysis

This chapter introduces different components that affect the design of the aircraft seat and headrest. This includes the cabin, the mechanisms of the aircraft seating market, an analysis of the product stakeholders (e.g. manufacturers, airlines, passenger), an analysis of headrests currently on the market and their problems, recommendations on headrest design concerning contact surface and a description of the importance of facilitating postures to comfort. It concludes by stating how these affect headrest and seat design. Demands based on this analysis are added to the programme of requirements that can be found in §7.3.

4.1 The aircraft cabin: an introduction

This project focuses on long haul flight, as these are the most strenuous to the passenger due to prolonged sitting of over 6 hours, often traveling through multiple time zones. Therefore seating comfort is more of a consideration to passengers than on short haul, and thus an important differentiation factor for airlines. Here a brief explanation is given of long haul flights and their on board amenities, cabin layout and seating differences per class.

4.1.1 Long haul flights

There are four classifications for flight duration (see Table 4.1), of which long haul and ultra long haul are of the longest duration, flying intercontinental. Aircraft flying these distances are generally wide body twin aisle aircraft (e.g. B787, B747, A380, etc.). Some airlines however replace the spokes-hub model (where passengers take a small aircraft to a hub-airport from where they take a big aircraft to their final destination) by the direct flight model with smaller aircraft, as these are easier to fill. On long haul flights classification (e.g. premium economy and business class) is more common, where on short haul flights sometimes only business class (BC) is offered. In general long-haul flights offer passengers more legroom than on short and medium haul, more recline and in flight entertainment (IFE). Depending on their duration, time of departure and arrival, there are one or more meal services, as are multiple drink/snack services.

Table 4.1 | Flight duration terminology

Duration	Terminology	Common distance
0-3h	Short haul	Domestic/ Continental
3-6h	Medium haul	Continental
6-12h	Long haul	Intercontinental
12+h	Ultra long haul	Intercontinental

4.1.2 Distractions from discomfort during flight

During flight passengers are limited in their personal space, movability, activity and privacy for a prolonged amount of time. The lack of freedom in activity and movement may cause physical and mental fatigue. Meal and drink services, IFE and sleep may help the passenger to distract from the obstructions and torment of air travel and to kill time. This might also be the reason why these activities are rated as very important by passengers (see §2.8). IFE for example helps a passenger to emerge into another world; being absorbed by the story, one is less conscious of its environment. Food and drinks not only provide in natural basic needs, they are also comforting and even social events to get acquainted with your neighbours. Keeping a good and friendly atmosphere within the cabin is not only key to keep passengers satisfied so they will fly the airline again, it may also plays an important role in cabin safety.

4.1.3 Cabin layout

The cabin layout is restricted by the available space in the pressurised compartment of the aircraft fuselage. The cabin layout comprises seats, crew rests and monuments (such as galleys, lavatories, closets, coatracks, etc.). The type of aircraft and regulations restricts the cabin layout. Roughly speaking there are two kinds of fuselage: narrow body and wide body. Narrow body features single aisle configurations, where wide body feature twin aisle. Some wide body aircraft such as the B747 and A380 offer two floor levels, of which the upper floor is reserved for business or first class (FC).

Although aircraft manufacturers (e.g. Boeing, Airbus and Embraer) may recommend a certain layout, airlines have the freedom to determine the actual cabin layout. Figure 4.1 shows a LOPA (Layout of Passenger Accommodations) of a wide body twin aisle aircraft with a three class configuration and Figure 4.2 a four class configuration. Classes are commonly located in descending order of class, from FC and/or BC at the front, followed by premium economy (PEC), if offered, and economy class (EC) in the back. The reason for this is that the more up front, the more quiet the cabin is, where especially the cabin area behind the engines (wings) is noisier. Premium cabin passengers are also located closer to the commonly used boarding door (left front), giving them first boarding and de-boarding privileges.

4.1.4 Seating positions, pith and configurations per class

Airline offers different seats in different configurations; with different recline options (e.g. some BC seats only recline up to 170˚, where others feature full flat beds), seating pitch (distance from one part of the seat to the same part on the next seat), seat width and configuration (e.g. 3-4-3 in economy, meaning three seats on the left and right and four in the middle). The amount of differences is quite extensive, but on average the following applies as shown in Figure 4.2. Not only the seat itself, but also the layout, position and separation of the cabin and the position of seats is important to the entire seat and flight experience, and thus should be considered in seat and cabin design.

Figure 4.1 | LOPA wide body twin aisle, three class Cathay Pacific Boeing 777-300ER (TripAdvisor LLC, 2018)

Figure 4.2 | Lower deck LOPA of wide body twin aisle, four class British Airways Boeing 747-400 V2 (TripAdvisor LLC, 2018)

Figure 4.3 | LOPA narrow body single aisle, two class British Airways Airbus A320 European (TripAdvisor LLC, 2018)

Table 4.2 | Common seating positions, pith and configurations per class for long haul flights (based on Torenbeek (1996) and TripAdvisor LLC (2018)). Differences among carriers apply.

Class	Recline options	Pitch (mean) [1]	Seat width (mean) [1]	Configurations
First class	TTL / Recline / Full-flat	42-90 (78.3) inch	18-36 (24.9) inch	1-2-1
Business class	TTL / Recline / Full-flat	30-82 (62,5) inch	17-34 (21.4) inch	1-2-1 / 2-2-2 / 2-4-2
Premium economy class	TTL / Far-Recline	29-47 (38.0) inch	16.5-21 (18.7) inch	3-3-3 / 2-4-2
Economy class	TTL / Recline	29-38 (32.2) inch	16-20 (17.6) inch	3-4-3 / 3-5-3

[1] Average based on TripAdvisor LLC (2018) SeatGuru database. When a seat measurement was given as a range, the mean was taken. Outliers were excluded.

4.2 The mechanisms of the aircraft seating market

As stated before, differentiation is important tool for airliners to gain market share. One of the main ways to differentiate is through the cabin, in where the seat plays an essential role since it is the part of the aircraft the passenger spends most time in.

When airliners order an aircraft – e.g. at Boeing, Airbus and Embraer – they also order its complete interior. This includes all the systems, monuments (such as galleys, lavatories and cabinets), cabin interior components (such as overhead bins and seats), inserts (such as trolleys, containers, life jackets) and many other components. The aircraft manufacturer takes care of bringing all components together, delivering a flight and commercially ready aircraft to the airline. To simplify this process, aircraft manufactures offer airliners so called 'catalogues', where can be choose from standard components with some limited customisability. These components are offered by third-party suppliers – such as Zodiac Aerospace – and are subject to extra requirements from the aircraft manufacturer (such as lead time and quality) to be considered offerable. Airliners however can also choose to source their cabin components outside the catalogue, to find products that meet their specific needs and help them to differentiate even more.

When looking specifically at seats, Airliners can order them in three different ways:

1) The first and most common option is to choose seats from the catalogue, compiled by the aircraft manufacturer (see 1 in Figure 4.4). Those seats on offer are standard with some standardised but limited options the airline can choose from (e.g. colour upholstery, IFE screen size, addition of tray tables, cup holders, etc.). For airliners this is very convenient; they only have to deal with the aircraft manufacturer.

2) The second and quite common option is to choose a standard seat directly from a seat manufacturer (even when a seat is not offered in the 'catalogue'), but request customisation (see 2 in Figure 4.4). This allows the airliner to create a more bespoke interior and experience. This however comes at a cost.

3) The third and least common option is to request a seat manufacturer to custom build an entire seat (see 3 in Figure 4.4). An airliner can order a custom design by the manufacturers in house R&D department or deliver its own design for manufacturing, e.g. developed by an external design agency (e.g. Lufthansa Technik, Jongeriuslab, PriestmanGoode). Such projects are costly and time intensive, especially since seat manufacturers are not able to sell the seat to other customers or with major revisions.

This mechanism puts most power in the hands of the aircraft manufactures, as they set the requirements for parts and production, and make the selection for the catalogue. Not being included (or taken out of the catalogue) can be catastrophic to seat manufacturers. For example, not being able to deliver seats on time will be fined by the aircraft manufacturer, as planes waiting for assembly cost both the aircraft manufacturer as the airline. When delivery problems continue, the seat manufacturer becomes *'non-offer-able'*, costing them a lot of business. Seat manufacturers also have to respond to the needs and wishes of airliners, which nowadays focuses more and more on improving comfort and luxury in premium cabins and weight and space reduction in economy cabins.
A new seat product should thus not only meet safety regulations and requirements, but also the requirements of the aircraft manufacturer should be kept in mind. Without their approval, success of a new product is less likely. These are especially important to consider in engineering and production of the final product.

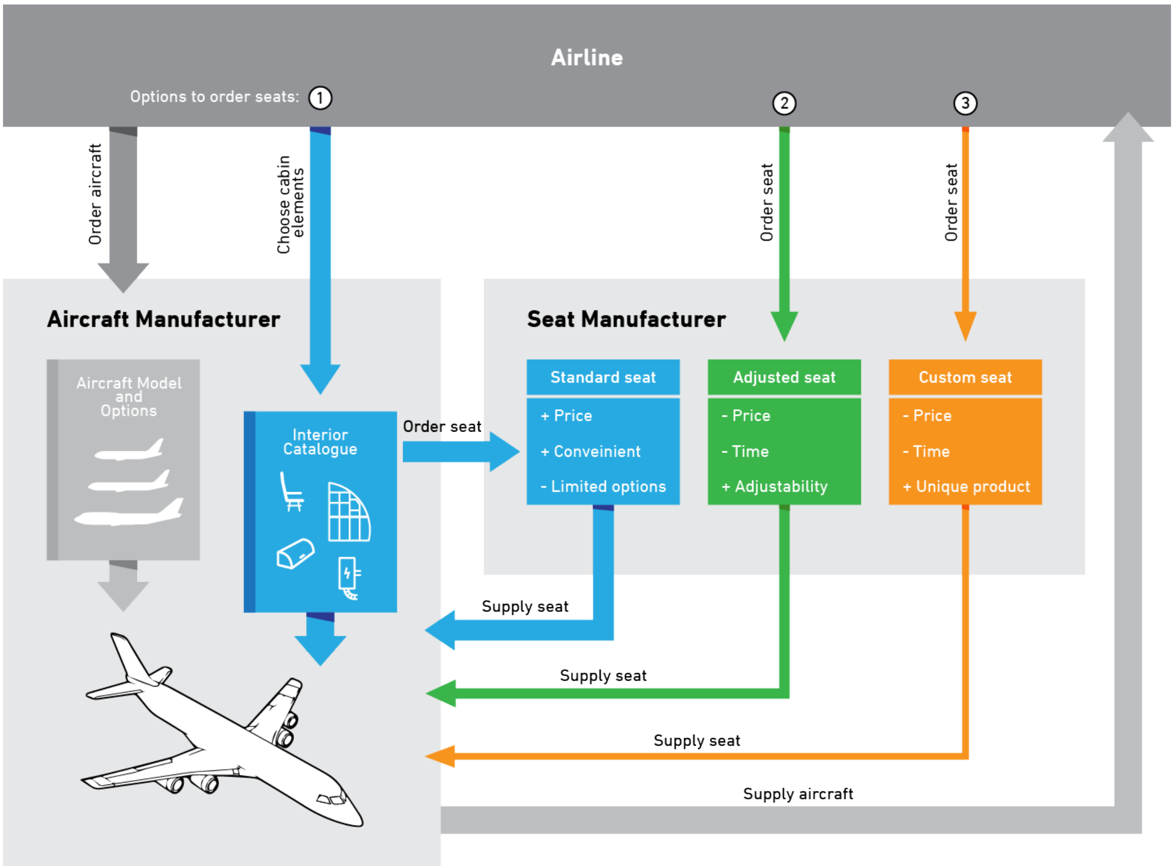


Figure 4.4 | Mechanics of ordering seats by airliners

4.3 Product stakeholders

When designing an aircraft seat and/or a headrest, multiple stakeholders and their interests and needs need to be considered. Based on own interviews with frequent BC passengers (n=12) (incl. the study by Vink et al. (2017) and Berghman et al. (2014)), work of Claussen and O'Higgins (2010), analysis of and interviews with caterers and cabin crew (n=12) (based on work at ZGEU), the following product stakeholders and their interests are determined:

4.3.1 The seat manufacturer

The seat manufacturer has to meet the requirements of aircraft manufacturers and the needs of airliners and passengers (see 4.2), while being profitable and differentiating from other seat manufacturers. The manufacturer is responsible for offering maintenance support and replacement parts to airliners. They are interested in a new product, feature and/or intellectual property (IP) to differentiate itself from competition and to sell to airliners.

To summarise, the following is important for the seat manufacturer:

- A new differentiating product
- Reliability and quality
- Meeting safety regulations

4.3.2 The airliner

The airliner want seating products that helps them to differentiate from the competition and adds value to the seat experience to justify ticket costs. They also want the headrest to be reliable, low in maintenance and having a long life span of at least 15 years (the lifespan of an aircraft seat). It is important that the headrest is easily replaceable without tools for a quick swap of a broken headrest, to minimise the impact on the turnaround time (time on the ground) and limit financial impact by guaranteeing continuity. For hygiene reasons, airlines want an easily replaceable dress cover for regular cleaning and replacement. And lastly the headrest should light, to safe on fuel costs.

To summarise, the following is important for the airliners:

- A new differentiating product
- Reliability and quality
- Meeting safety regulations
- Light weight (to safe on fuel)
- Quick replacement (to minimise turnaround time)

4.3.3 Type of premium cabin passengers

The premium cabin passenger is in the end the final stakeholder, the client of the airliner and the user of the product. Premium cabin passengers can be divided into five categories, where the '*corporate traveller I'* has two slight variations:

- *Upgrader – Leisure and corporate travellers who use loyalty program points or auctions to get upgraded from EC to PEC or BC. This target group is highly sensitive to prices and loyalty schemes, and less sensitive to flight frequency.*
- *Affluent leisure traveller – Travels purely for leisure and their choice for BC is more wellness related. Their reason to fly BC is for the perks (good dining, improved flight experience, privacy) and the comfort of better seating and sleeping, to land refreshed. They fly often with their spouse, but also travel alone regularly. They look for both attractive pricing (e.g. early booking) and scheduling.*
- *Corporate traveller I – Medium to high-level executives, who travel frequently for business. Flight frequency, a strong airline network, a high quality product (to land rested and refreshed, so they can go immediately to work at their destination) and attractive loyalty programmes are important to them. They mainly fly business class and are less sensitive to price, as the company pays for it. They often do some work-related reading during flight and some work on a laptop, but mainly make use of the otherwise 'lost time' to get a good rest (IFE/sleep) in preparation of work at the destination and in preparation of the effects of time-zone differences. They mainly fly alone, sometimes with a colleague or spouse.*
    - *The workaholic – Works a lot, has dinner with IFE and catches some sleep in the end.*
    - *The acclimating business traveller – Mainly relaxes (reading book, chatting, watching IFE) and sleeps, so they can go directly to work when they land.*
- *Corporate traveller II – Middle level employees travelling for business purposes. They do not travel in premium cabins, unless the price is reasonable, due to price limitations by their employer. These travellers often collect their loyalty program points from business trips for leisure purposes, take their spouse with them or upgrade to premium cabins.*
- *Self-employed – As these business travellers mostly pay for their own flights, they are more price conscious and look for a good quality/price trade-off and are willing to schedule their trips according to available cheap offerings.*

To summarise, the business class passenger:

- Expects a comfortable experience during flight.
- Expects a comfortable full flat bed sleep.
- Expects to have a comfortable IFE experience.
- Does not want to be limited in activity and posture.
- Expects adequate support and adjustability of the seat.
- Want easy understandable controls of the seat.

The Premium Economy passenger:

- Wants the second best comfort experience during flight.
- Expects better sleeping comfort than in EC, e.g. by a further seat recline.
- Expects a better IFE experience, e.g. by a bigger screen and further seat recline.
- Want easy understandable controls of the seat.

4.3.4 The cabin crew

Although not directly sitting in the seat, cabin crew are stakeholder as they interact with seats. They have for example assist passengers with finding and operating functions of the seat, deal with problems of e.g. damaged components and find lost items within the seat (BC FA, 2015). It is thus important for them to have a reliable product, which requires minimal to no instructions from the crew to operate.

To summarise, the following is important for cabin crews:

- A good overview over the cabin. Headrests, IFE screens and other seat features may not obstruct cabin view.
- Easy to use (clear usecues, minimal instructions), reliable and safe headrest, to have minimal questions, problems and/or complaints related to seat use by passengers.

4.3.5 The cleaning staff

After disembarking the passengers, cleaning staff and catering staff will enter the aircraft, where cleaning staff are responsible for cleaning and distribution of new blankets and pillows in the cabin, where caterers responsible for replacement of items (e.g. trolleys and containers) and providing new supplies to the cleaning staff for in cabin distribution (e.g. blankets, pillows, waste bags, magazines, etc.). Cleaning staff will interact with the seat and headrest as such that they need to be able to clean them quick and easily and replace dress covers and antimacassars (replicable cloth on the headrest for hygiene purposes) (Forgatsch & Lohrmann, 2016).

To summarise, the following is important for cleaning staff:

- Easy to clean.
- Easily replaceable antimacassar.
- Easily replaceable dress cover for regular cleaning and replacement.

4.3.6 The maintenance engineers

Aircraft seats and their headrest need to be maintained. Due to intensive use and abuse products, wear and break down, requiring replacement and repair. Durable, minimal to no maintenance requirements (e.g. lubrication), easy and quick replacement and easy serviceability are important for maintenance engineers to keep aircraft up and running (Forgatsch & Lohrmann, 2016).

To summarise, the following is important for maintenance staff:

- Easily replaceable headrest without tools for a quick swap of a broken headrest, to minimise the impact on the turnaround time and limit financial impact by guaranteeing continuity.
- Easy access to and replacement of parts
- Wants minimal amount of different parts in stock. Thus preferably use standardised parts and minimal use of unique.

4.3.7 Governmental aviation agencies

Governmental agencies (such as the FAA in the U.S.A. and EASA in Europe) are responsible for the making and enforcement of safety regulations and part certification, with the aim to keep flying safe. Aircraft manufacturers, airliners and suppliers such as seat manufacturers have to meet their strenuous requirements. Without certification, a part or a product, such as a headrest, may not fly.

To summarise, the following is important for governmental aviation agencies:

- Safe and certified products, meeting certification standards or sustaining certification tests.

During this design project the requirements are kept in mind (see §7.3), but not strictly followed, as this will limit creativity (Schultheis, 2016a). Products that do not meet current requirements can get certified when they meet standardised safety tests. Although these tests are expensive for seat manufacturers, this gives room for innovation.

4.4 The state of the art of headrests

The headrest in an aircraft has two main functions; provide support when sitting and reclining and prevent a head and neck injury on impact (e.g. a rough landing or crash). As aviation is very engineering driven, head rest have been simple and maybe even overlooked parts of the aircraft seat as a way to improve comfort (Durston, 2013). The introduction of flick-out flaps on the headrest offer some support when sleeping, but not adequate. In this section the current standard aircraft headrest, a selection of competing 'new generation' headrests and issues with current headrests are discussed.

4.4.1 An impression of a standard headrest

In aircraft most headrest are relative simple components. Their frame is from an aluminium sheet with perforated holes to save weight (see Figure 4.5). It is connected on the seat backrest by a friction slider rail, allowing height adjustment. On the sides of the aluminium frame are two friction hinges connected, each holding an aluminium plate forming the flick-out flaps. On the frame velcro is placed, to attach the foam piece. This is a subassembly containing a hard foam cover piece at the back to prevent the passenger to touch the aluminium frame with the head, followed by a softer contact foam and is completely covered with a fire-retardant liner. To keep all the parts together and clean, a dress cover is placed over the entire headrest assembly and fixated with velcro.

4.4.2 Current competing headrests

As it is impossible to describe all variances, a selection was made of headrest that are most promising for sleeping and watching IFE within the aircraft, or might even directly compete with the final design of this project.

The *HeadRest* by Manon Kühne (TU Delft/ZSUS) (see Figure 4.6) is an economy headrest featuring flick-out flaps with a hammock inside allowing passengers to rest their head inside to prevent sliding and nodding when sleeping upright. Side flaps at eye height provide extra privacy. This product is relative light, simple and cheap. There are however issues with the hygiene (e.g. drooling on the dress cover).

The Six-way headrest by Cathay Pacific (see Figure 4.7) is an economy headrest featuring fold-out flaps with a hammock inside allowing passengers to rest their head inside to prevent sliding and nodding when sleeping upright. The design is slightly similar to that of the HeadRest in functionality. There are reports the headrest has durability and reliability issues and the dress cover is hard to replace and clan (Anonymous, 2016).

The headrest of the CL3710 by Recaro Aircraft Seating (see Figure 4.8) is a flexible economy headrest. The headrest can articulate up and downward to facilitate a wide range of passenger heights. For neck support, a neck bolster can be pulled outwards. And for sleeping the headrest can be curved to create a slight shell shape. It however does not prevent sliding and nodding of the head when upright sleeping.

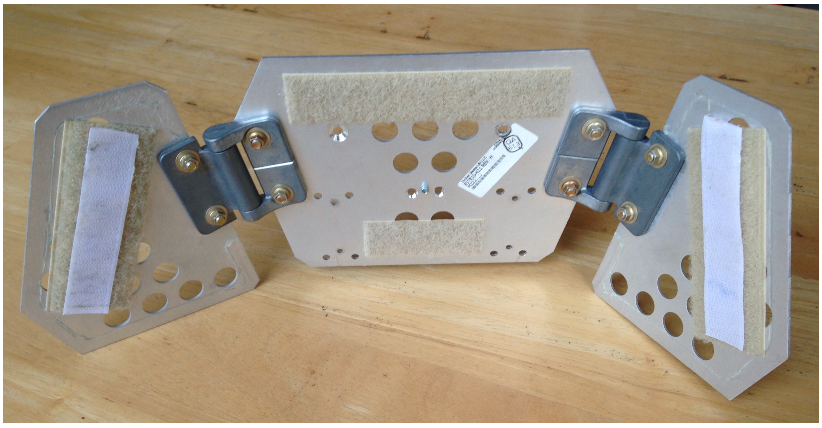


Figure 4.5 | Aircraft seat headrest frame, made of aluminium punched sheets, friction hinges, nuts, bolts, locking rings and velcro.

Figure 4.6 | HeadRest by Manon Kühne (TU Delft/ZSUS)

Figure 4.7 | Six-way headrest by Cathay Pacific

Figure 4.8 | CL3710 headrest by Recaro Aircraft Seating

4.4.3 Impressions of headrest issues with current aircraft seats

In the analysis of existing headrest, two main issues stood out: the protrusion of headrests, putting stain on the neck or causing bad postures, and the insufficient height adjustability. These are further explained below in more detail. It is important to consider these issues in designing a headrest.

4.4.3.1 Protruding headrest and lack of free shoulder space

A lot of current headrests seem to protrude too much forward (see Figure 4.9). When passengers lean against the backrest, their shoulders, neck and head get pushed forward. To counteract the pushing force, extension muscles in the neck (e.g. m. splenius, m. semispinalis and m. trapezius pars descendens) probably have to contract to maintain 'stability' of the head. This prolonged contraction may lead to muscle fatigue and discomfort. Passengers may for example also slump forward to relieve the neck (which was observed during a 10h flight from LHR to DFW and stated by cabin crew in interviews, see also Appendix H), taking a bad posture and putting strain on the lower back by curving their lumbar convex, compressing the intervertebral discs and straining back muscles. In a survey by Quigley, Southall, Freer, Moody, and Porter (2001) passengers stated headrest were pushing too much forward, were too high or not high enough and did not provide adequate support. Goossens, Snijders, Roelofs, and Buchem (2003) show that free shoulder space – the distance between the tangent to the lumbar support and the parallel tangent to the scapulae (shoulder) support – of at least 6 cm will decrease back muscle activity and allows for lumbar support. The pilot study of Coelho and Dahlman (2012) however suggest that in the context of driving a car, a protruding headrest is more comfortable.

One would expect that no head support by a headrest is needed when sitting upright, as people in other context (e.g. sitting in the office, walking, cycling, etc.) are perfectly capable holding the head up for a prolonged amount of time. Our neck extension muscles (m. splenius, m. trapezius, etc.) are strong enough to keep the head - which tends to fall forward as the gravitational point of the head is in front of the atlas (pivoting point in the cervical spine) - upright. Head support makes more sense when we lean backwards. That is the time when we want to have the weight carried by the seat, to prevent the having to carry the full weight of the ~5Kg head, especially when it is not trained to sustain prolonged contraction. As literature is inconclusive, further research on the effect of headrest protrusion is advised. For the time being limiting protrusion of headrests is advised.

4.4.3.2 Headrest support for ~P5-P95, facilitating a larger population

Most current headrests on aircraft seats have limited height adjustability and therefore a part of the population is excluded of proper use. Especially for tall passengers the limited adjustability of the headrest is bothersome, as it may push at the shoulder area making them take uncomfortable or bad postures by bending or slumping forward (see middle example of Figure 4.9). Height adjustability is thus very important for the comfort experience of the head, neck and shoulder area. To facilitate both a P5 Asian female and a P95 Dutch male (Vink & Brauer, 2011), a headrest adjustability of 270mm is needed (see Table 4.3). Other data in this table are relevant to consider in headrest design.

Figure 4.9 | Left: Virgin Autralia domestic-business class seat with protruding headrest. Middle: Z600 domestic-business class seat with protruding headrest. Right: an ZSUS economy class seat where the headrest has a slimmer profile as the backrest provides an indented space.

Table 4.3 | Antropometrics of P5 Asian female, P50 and P95 Dutch male. DINED data from J. F. Molenbroek (2004).

Population	International South East Asia, female	DINED2014 Dutch adults 20–30, female	DINED2014 Dutch adults 20–30, male	DINED2014 Dutch adults 20–30, male
Percentile	P5	P5	P50	P95
Sitting height (mm)	**751**	829	957	**1021**
Eye height, sitting (mm)	661	726	842	906
Head breadth (mm)	127	136	152	162
Head depth (mm)	165	176	199	211
Shoulder height (mm)	n.a.	534	624	680
Shoulder breadth (bi-deltoid) (mm)	345	384	470	511
Hip breadth, sitting (mm)	330	358	388	436

4.5 Headrest pressure distribution and profile

When designing a headrest, it is important to determine its shape and padding, as it comes in contact with and supports the head, neck and face. The jaw, the back of the head and temple (upper part of the skull) are ideal contact area's to carry load of the head on the headrest. Soft and sensitive tissue as the cheeks, ears and neck should have soft contact, especially as these will have direct contact with the headrest and they are not covered by clothing (Franz, Durt, Zenk, & Desmet, 2012; Harrison, Harrison, Croft, Harrison, & Troyanovich, 2000; Rotte et al., 2014). An estimation is shown in Figure 4.10, based on Franz et al. (2012) and Rotte et al. (2014). Exact maximal pressure between the head and headrest with the lowest given discomfort can be found in Table 4.4.

In a study by Y. Lin and Huang (2007) (n=30), a pillow with neck support lowered muscle tension in the sternocleidomastoid over time in a upright posture. Franz et al. (2012) found for in a car seat that approximately 80% of passengers appreciate neck support, where 20% does not. Similar results can be found in pillow studies (Ambrogio, Cuttiford, Lineker, & Li, 1998; Persson, 2006). Shields, Capper, Polak, and Taylor (2006) found that some subjects may initially find cervical pillows uncomfortable, but tend to accept them after an extended period of use. However, Gordon, Grimmer-Somers, and Trott (2009) found no evidence that the use of a foam contour pillow has advantages over a regular shaped pillow. As preferences in neck support are different, passengers should thus be offered the possibility of having neck support or not. A relative soft, not too high and firm neck support for cervical lordosis is advised for a flat sleeping position (Liu, Lee, & Liang, 2011; Persson & Moritz, 1998; Yim, 2015). This might also be applicable in upright and slouched seating.

Nijholt, Tuinhof, Bouwens, Schultheis, and Vink (2016) and Hiemstra-van Mastrigt (2015) give contours of the head with big variations, making it difficult to give an ideal profile. Franz et al. (2012) too found variations in distance between the back of the head (akromion) and most forward part of the back of the neck (concave apex), as shown in Table 4.5. This indicates that adjustability of the headrest both in height and neck support is needed.

4.6 The importance of posture allowance to comfort

Activities performed during flight are associated with postures the passenger takes (Ellegast et al., 2012; Groenesteijn et al., 2012; Groenesteijn, Vink, de Looze, & Krause, 2009; Hiemstra-van Mastrigt, 2015; Kamp et al., 2011; Smulders et al., 2016; Vink & Hallbeck, 2012). Having the freedom to re-sit and change posture frequently (Lueder, 2004; Van Dieen, De Looze, & Hermans, 2001; van Rosmalen, Groenesteijn, Boess, & Vink, 2009) and having adequate possible for these postures (Kamp et al., 2011; Yun, Donges, & Freivalds, 1992) may increase comfort and decreases discomfort (Konijn, Jongejan, Berger, & Vink, 2008). As the shape of a seat largely determines the assumed body posture (Snijders, Nordin, & Frankel, 1995) an activity based seat design can improve passenger experience (Bronkhorst & Krause, 2005). It is important to facilitate these activities on an individual level (Clarkson, 2008), as passengers desire different activities, which require different conditions (Bouwens, 2017). A new headrest/seat design thus should be posture focussed, facilitate multiple postures and activities and provide (individual) adjustability.

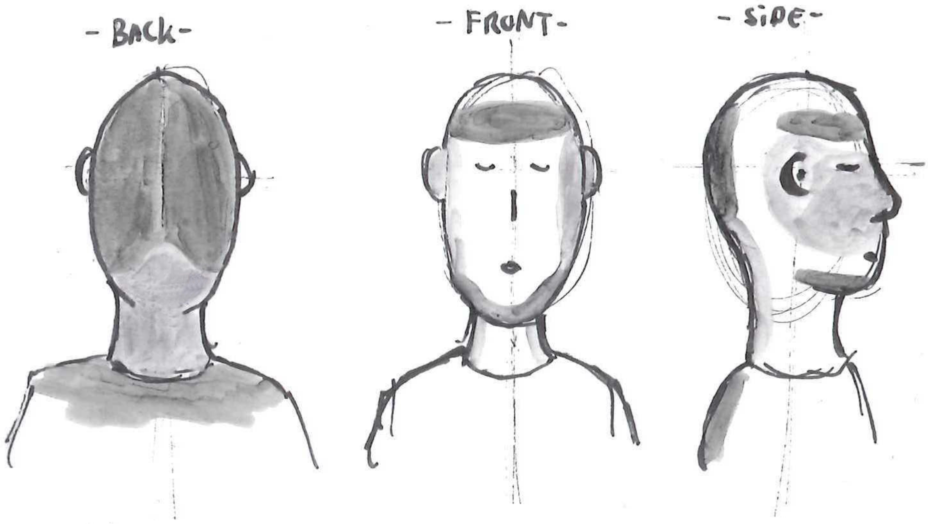


Figure 4.10 | Estimation of sensitivity of the head per area based on Franz et al. (2012) and Rotte et al. (2014). Light grey is more sensitive tissue that preferably should be in contact with soft materials. Dark grey is less sensitive and can carry loads.

Table 4.4 | Maximal pressure between head and headrest with the lowest discomfort score per region (Franz et al., 2012)

Body region	Maximal pressure
Head	1,8 KPa - 3,7 KPa
Neck	< 1 KPa
Shoulder	2-7,6 KPa

Table 4.5 | Distance between the back of the head (akromion) and most forward part of the back of the neck (concave apex)

Source	Sample size	Condition	Population	Shortest distance (mm)	Average distance (mm)	Largest distance (mm)
Franz et al. (2012)	n=35	Car seat in upright position	Men	3		27
			Women	10		37
Nijholt et al. (2016)	n=46	Economy aircraft seat watching IFE in upright position	n.a.		21 [1]	

[1] Reanalysis of given data in publication. Given measurements are and estimation.

4.7 Conclusion

Business class (BC) and especially premium economy (PEC) seats on long haul flight differ among carriers. However, most new generation seats offer in BC full flat sleeping capabilities and extended recline in PEC. This is important to consider in headrest design for both sleep and watching IFE.

The previously described stakeholders show that many interests need to be taken into account. The main stakeholders for a new headrest product are the airliner and passenger, as they are the final users and 'buy' the product. The airliners want a differentiating product for their cabin to persuade premium cabin passengers, where the passengers look for a comfortable flight experience. The product thus should focus on improving comfort. Other important stakeholder requirements to consider are the easy and minimal maintenance, quick replacement (without tools), clear usecues, replaceable antimacassar and dresscover, no obstruction of cabin view and ingress and egress of the seat and meeting safety FAA requirements.

Although some new generation headrest make improvements, most current headrests provide insufficient support for sleep and watching IFE, protrude and are limited in height adjustability and thus limited in offering support to a wide population. A new headrest design thus should improve on these issues. Height adjustability of the headrest is important for the comfort experience of the head, neck and shoulder area. An articulation of 270mm is recommended to serve a wide population of a P5 Asian female up to a P95 Dutch male. A slim headrest profile is recommended to give free shoulder space to passengers. As it comes down to the contact between the head and the headrest, it is important to support on the back of the head, at the temple and jaw line, where area's of the neck, cheeks and ears should have soft contact only. It is advised to offer neck support, as it is perceived as more comfortable and may lower muscle tension, but it should be adjustable as not all passengers like it.

Lastly, the new headrest design should be posture focussed, facilitate multiple postures and activities and provide (individual) adjustability. As stated in chapter 3, the focus of the design will be on IFE and sleep, as these are among the most conducted activities in transit (see §2.8).

To make passengers feel at home in their seat, insight is needed on how people sleep and watch TV at home, what postures they take and what preferences they have. This will be explored in the next chapters 5 *Sleeping comfort in transit* and chapter 6 IFE comfort in transit.

4.7.1 Main headrest challenges:

- Prevent headrest to push the head forward (e.g. in TTL).
- Durability, especially of height adjustment mechanisms.
- Hygiene, as headrests come into contact with skin, sweat and other body fluids (e.g. trough the use of an antimacassar).
- Usecues of headrest adjustability (height adjustment, support by 'wings', forward bending, etc.).
- Height adjustability of ~270mm, supporting as close as possible to Asian P5 female and Dutch P95 male.
- Facilitate multiple postures.

4.7.2 Important to consider headrest design:

- Simplicity; complexity ads weight, durability and maintenance issues.
- Finger ('fingerpinching') and hair safety.
- Fire retardant materials.
- Comfortable and breathable materials.
- Replaceable without tools.
- Easy to maintain.
- Headrest cover easily replaceable for regular cleaning.
- Ergonomic headrest shape.

4.7.3 Recommendation for further research and development

It is recommended to further research the effects of protruding headrests on neck biomechanics (muscle activity), the effect on taken posture and comfort, as the hypothesis is that a headrest that is in line with the backrest is more comfortable and results in less strain on the neck muscles.

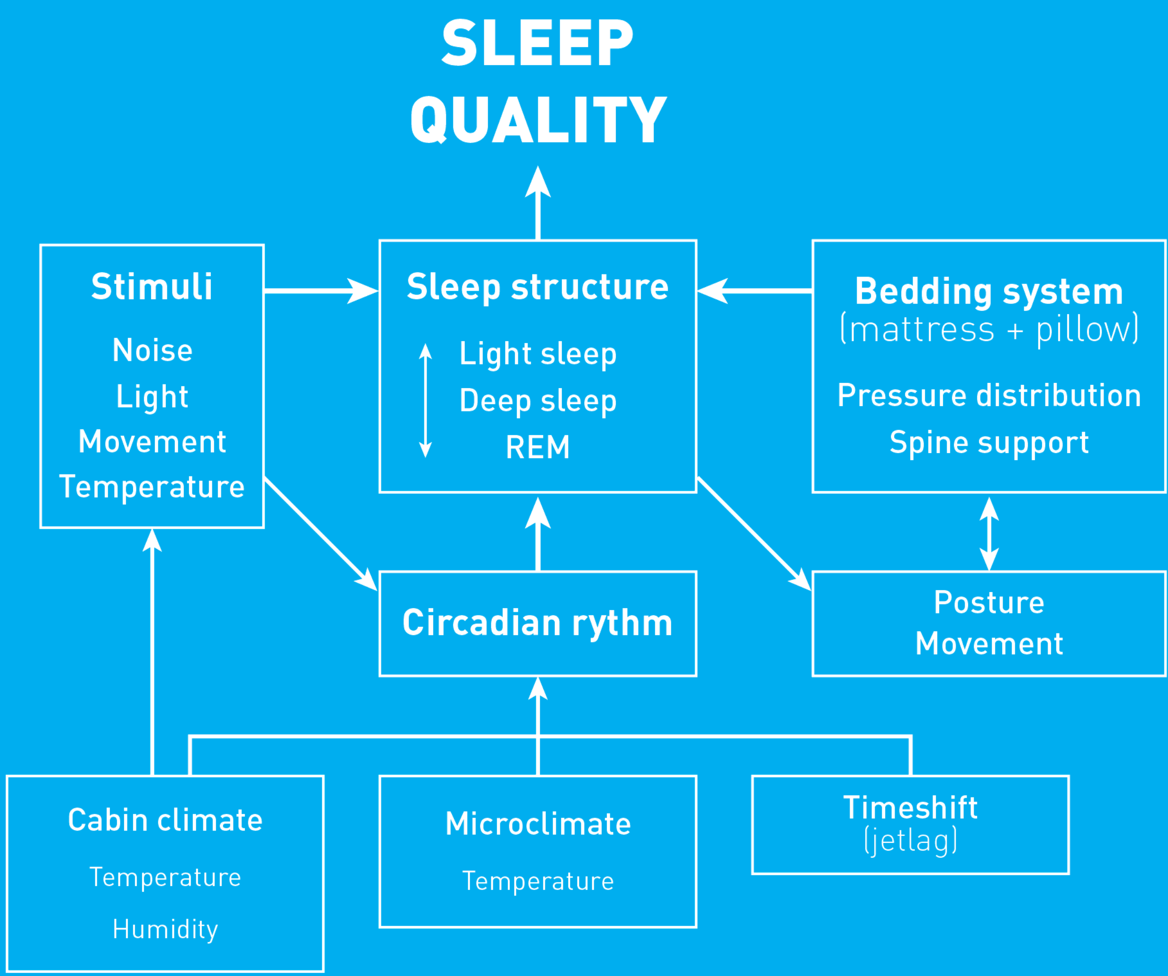
4.8 Further reading

For a comprehensive overview of the aviation and seating context, Vink and Brauer (2011) *Aircraft interior comfort and design* is recommended. For further reading on seating anthropometrics Molenbroek, Albin, and Vink (2017) *Thirty years of anthropometric changes relevant to the width and depth of transportation seating spaces, present and future* and Quigley et al. (2001) *Anthropometric study to update minimum aircraft seating standards* are advised.

4.9 Recommendations for seat manufacturers

The consideration, exploration and/or implementation of the following recommendations – based on previously discussed sections – are advised:

- Slim headrest profile. No contact when sitting upright with head upright ('airgab') is advised. Only when tilting head backward or adjusting headrest for IFE/sleep support is needed. [§4.4]
- Height articulation of 270mm. [§4.4]
- Cary the load of the head at the back of the head, temple and jaw line. [§4.5]
- Have soft contact at the neck, cheeks and ear. [§4.5]
- Adjustable neck support, so the passenger can choose the intensity. [§4.5]
- Facilitate multiple postures [§4.6]



Chapter 5 **Page**

5 Sleeping comfort in transit

As stated in the previous chapter, facilitating activities within the aircraft seat is important to comfort. As sleeping is – like watching IFE – one of the major activities during long haul flights, this chapter explores sleep and the context factors influencing sleep, such as rhythm, temperature, stimuli and posture (see Figure 5.1). These factors pose both challenges and opportunities that can be used or should be taken into account in a new headrest and seat design.

← Figure 5.1 | Factors influencing sleep (Based on Verhaert, Haex, Wilde, et al. (2011) and own insights)

5.1 A note on the knowledge gab

We spend approximately one third of our life in bed. 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 your sleep cycle – until 1953, simply because technology was not ready to measure brainwaves accurately enough. Most research on sleep has been conducted from a medical perspective (Kryger, Roth, & Dement, 2016; Lee-Chiong, 2010); the quality of sleep and bed ergonomics is an even younger field of study (Coenen, 2006; Haex, 2005). Currently a lot of claims on the influence of psychological, physiological, and physical conditions on the quality of sleep – mostly made for promotion purpose of manufacturers – lack actual scientific suppor (Coenen, 2006; Verhaert, Haex, Wilde, et al., 2011). Especially the physical (environment, bed, mattress, linnen, pillow, etc.) impact on sleep quality is relatively underexposed in science. Despite the limitations, care is taken to state scientific funded insights in this chapter on improving sleep quality and the related bed ergonomics.

5.2 Structure of sleeping

To create a comfortable bed-seat in the aircraft for sleeping, it is important to get a good understanding of the structure of sleep and its properties. On average we sleep seven to nine hours per night (Carskadon & Dement, 2017; Coenen, 2006; Kripke, Simons, Garfinkel, & Hammond, 1979). During our sleep we go through a cycle of five stages of sleep multiple times a night; stage 1 till 4 (nonREM) and REM (see Table 5.1 and Figure 5.2). The first part is when you get into your bed and actually fall asleep – which mostly goes quickly – into stage 1 (S1): a light sleep where you drift in and out of sleep. The eyes will move slowly and muscle activity slows down. This is also a moment where one can easily be awakened. This stage takes between five to fifteen minutes and is a reasonable predictor of the quality of sleep; the shorter stage 1 the better the sleep (Coenen, 2006). Stage 1 is quickly followed by stage 2 (S2), where eye movement stops and brain waves become slower. Here sleepers become gradually harder to get awaken. Stage 2 quickly transits into stage 3 and 4 (S3 and S4, in modern USA literature often combined as stage N3, as defined by the American Academy of Sleep Medicine (Carskadon & Dement, 2017)), which is deep sleep (a.k.a. slow wave sleep; SWS). In this phase it is very difficult to wake someone. In deep sleep, there is no eye movement or muscle activity. The sleeper is less responsive to the environment; many environmental stimuli no longer produce any reactions. Deep sleep is thought to be the most restful form of sleep, the phase which most relieves subjective feelings of sleepiness and restores the body (Waterhouse, Fukuda, & Morita, 2012), due to the production of growth hormones (Coenen, 2006). After some time in stage 3 and 4, we go via stage 2 into REM. In REM the muscle tension is very low, eyes move quickly and it is the stage we dream in. Although its function is still not clear, the science community expect it has something to do with cognitive (memory) and emotional recovery (Coenen, 2006; Van Deun, Verhaert, Willemen, Haex, & Vander Sloten, 2012). During REM the body temperature regulation shuts down by the complete relaxation of muscles. Due to its short duration of 10-15 minutes, its all-over impact on the body temperature is limited (Coenen, 2006). Sleep ends by going by the end of REM into awake (Åkerstedt et al., 2002). It is also easier and better to get woken from REM opposed to SWS (Dinges, Orne, & Orne, 1985; Langford, Meddis, & Pearson, 1972) or S2 (Cavallero & Versace, 2003), as awakening from SWS or S2 (NREM) will cause sleep inertia. However, elderly are as likely to spontaneously get awaken from REM as from S2 (Salzarulo et al., 1999).

Table 5.1 | Stages of sleep (inspired by Crean (2015), based on Carskadon and Dement (2017); Coenen (2006); Fuller, Gooley, and Saper (2006); Iber, Ancoli-Israel, Chesson, and Quan (2007); Waterhouse et al. (2012))

Phase	Awake (W)	NREM				REM (R)
		Light sleep		Deep sleep (N3/SWS)		
		Stage 1 (S1/N1)	Stage 2 (S2/N2)	Stage 3 (S3)	Stage 4 (S4)	
Consciousness	Fully conscious	Conscious awareness of the external environment gradually disappears	Complete loss of conscious awareness	Difficult to wake someone. If so, that person will feel disoriented for a few minutes		Most vivid dreams happen in this stage
Brain waves	Normal	Slows down	Slows down, with occasional bursts of rapid waves	Very slow brain waves (delta waves), interspersed with smaller, faster waves		Similar to awake
Eyes	Open	Eyes move slowly	Eye movement stops	No eye movements.		Rapid eye movements
Muscles	Active	Activity decreases	Low activity	No activity		Atonic, with incidental muscle contractions
Other characteristics	Responsive to external stimuli and can hold intelligible conversation	Drowsiness. Low arousal threshold; easy to wake up	Heart rate, breathing and body temperature decreases in preparation for SWS	Release of growth hormones and restore immune system		Heart rate and breathing increases, no thermal regulation.
Duration of total sleep		2-10%	45-55%	10–25%		20–25%
Important		*One can easily be waken up.* *The shorter, the deeper the sleep will be.*		*Physical recovery by production of growth hormones and muscle relaxation*		*Mental recovery*

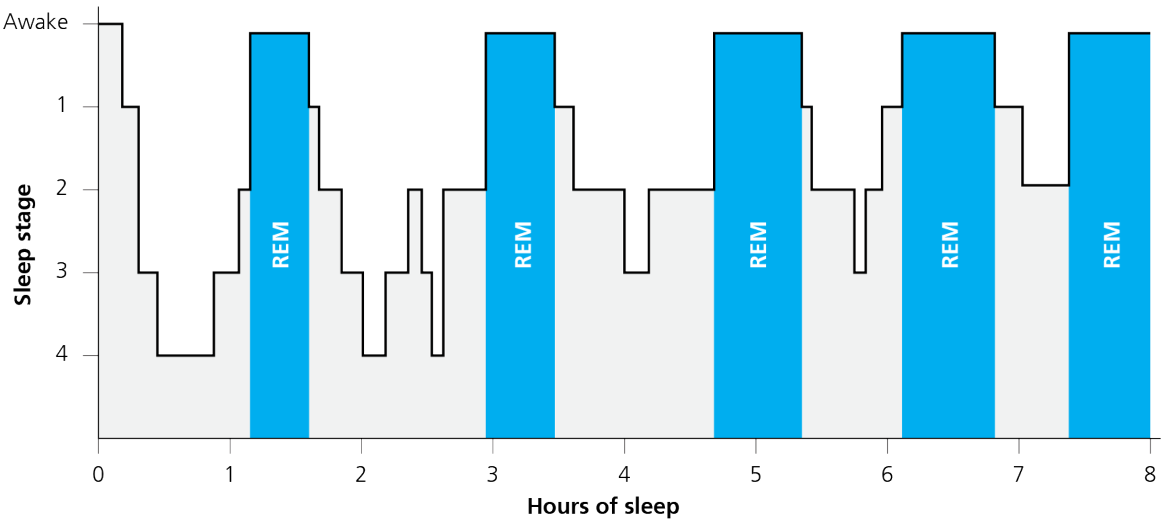


Figure 5.2 | Typical eight hour sleep cycle

5.2.1 Determining sleep stage (based on movement, respiratory and heart rate)

Determining sleep stages with the aircraft seat can help to 'manage' the sleep cycle with temperature, light and sound, e.g. waking the passenger up just after a REM cycle close before a cabin service or landing. This is better, as people feel disoriented when woken up from other stages, especially SWS (Dinges et al., 1985).

A normal human adult enters sleep through NREM, followed by REM after 80 min or later. After the first REM cycle, NREM and REM will alternate through the night in approximately 90 min cycles (Carskadon & Dement, 2017; Coenen, 2011). Although on average sleep stage based on time might work, humans and their sleep cycles are different, especially in the aircraft. The sleeping conditions in the aircraft are not ideal; strange environment, noise, light pollution, limited to no privacy, etc. make it hard to get a qualitative sleep. Therefore, assuming aircraft passengers sleep in steady 90 minutes cycles might not reflect a real world scenario. Movement, respiratory and heart rate are better indicators of sleep stages of passengers than time in the context of aircrafts.

Wilde-Frenz and Schulz (1983) shows strong relationship between body movement and sleep stage, with the rate of body movement decreasing along the following order of sleep stages: W > S1 > REM > S2 > SWS (S3+4). Gori et al. (2004) found similar results among young subjects. Muzet, Naitoh, Townsend, and Johnson (1972) shows that movement during sleep can be an indicator for sleeping stage, as in S2 the last ten minutes before SWS in 86% of the epochs no movement occurs, where in 80% of the epochs movement occurred before REM. See also Figure 5.3, which shows body movement during sleep of a young adult, where movement occurs before and during REM. However, Gori et al. (2004) shows that correlation between movement and sleep stage is age dependent, as no specific sleep state and/or stage was preferentially associated with the occurrence of body movements in the elderly. However, a higher percentage of body movements were associated with a sleep stage change or by a spontaneous behavioral awakening in the following 60 seconds. Willemen et al. (2012); (2014) shows the possibility to automatically determine sleep stages based on easy to register signals such as heart rate, breathing rate and movement by an algorithm with an accuracy of 94% on their test dataset. This can be useful to implement within an aircraft seat (see §8.1.1 for an example).

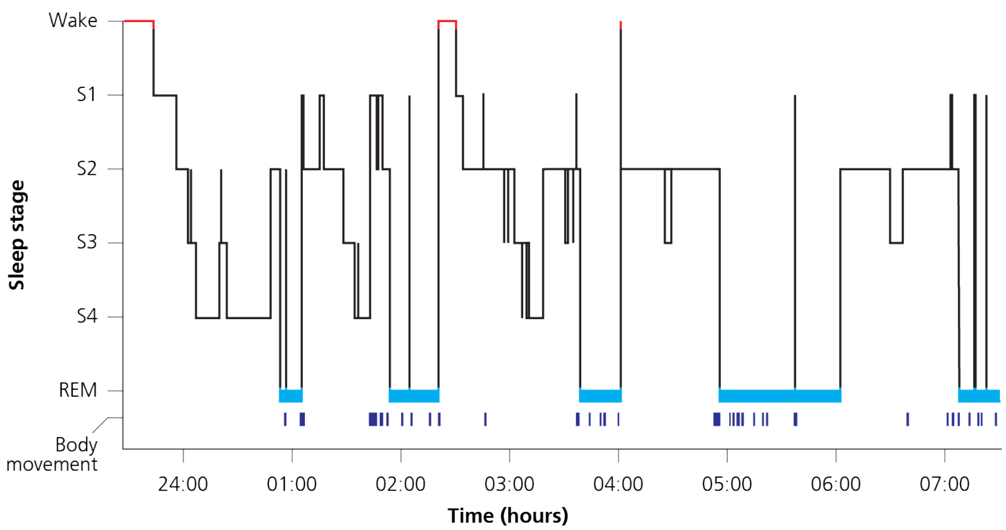


Figure 5.3 | Sleep histogram of a single night in a normal young adult volunteer, progressing through the different sleep stages and showing recorded movement mainly during REM sleep (from Carskadon and Dement (2017)).

5.3 Circadian rhythm and the influence of temperature on sleep

Besides the structure of sleep, also the natural rhythm of sleep needs to be considered for sleeping in the aircraft. Our sleep and wake cycle is circadian; it is synchronised with the alternation of day and night. Light and temperature are dominant environmental time cues that entrain the human circadian clock (Waterhouse et al., 2012; Wright et al., 2013). The human body temperature follows this circadian rhythm (Waterhouse et al., 2012), as can be seen in Figure 5.4. Also timing of light exposure will influence shifts in of the circadian clock (Drake & Wright, 2011).

The human body wants to sleep when it is dark and the body core temperature is falling or low (evening and night), where the body wants to be awake when there is light and the temperature is rising or high (Blake, 1967; Coenen, 2006; Raymann, Swaab, & Van Someren, 2005; Waterhouse et al., 2012). Spontaneous awakening tends to be easier when the body core temperature rises and is difficult when its low (Waterhouse et al., 2012). Normally our temperature-rhythm (which adapts slowly) and sleep-wake system (which is more flexible) are synchronic. Disturbing these cycles may result in jetlag symptoms (see §5.3.3). Thus controlling temperature and light with in the cabin (§5.3.1) and aircraft seat (§5.3.2 and §5.3.3) are important for falling asleep, keeping asleep and waking up.

5.3.1 Cabin/room temperature

As controlling temperature with in the cabin can positively influence sleep, it is important to determine adequate temperature ranges. Ideal temperature values stated in literature deviate, but on average a room temperature between 16-18°C is advised. A relative cool environment prepares the body for sleep. At higher temperatures it is difficult to lose body heat, so the necessary temperature drop during sleep cannot be done properly. The body will sweat to cool down, which will feel uncomfortable (Coenen, 2006; Muzet, Libert, & Candas, 1984; Onen, Onen, Bailly, & Parquet, 1994). The duration of wakefulness increases and duration of NREM and REM decreases when sleeping in a warm environment (31-38°C) (Kräuchi, Cajochen, & Wirz-Justice, 1997).

The room temperature should also not go below 12°C, as the body will have difficulty to stay warm. The body will shiver to increase its temperature, which will feel uncomfortable (Coenen, 2011). Cold exposure induces more awaking time and less stage 2 (S2) sleep, but does not affect other sleep stages (Kräuchi et al., 1997). It also may make people wake up, requires thicker and heavier blankets or clothing to keep warm that limits movement, which have a negative impact on the comfort during sleep (Coenen, 2006; Onen et al., 1994). ▸

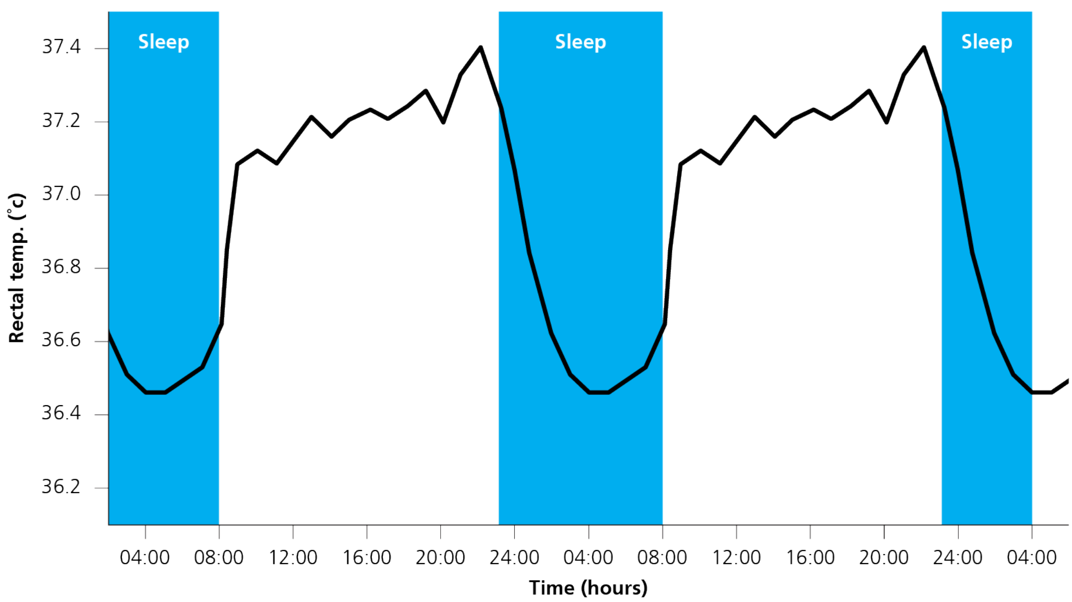


Figure 5.4 | Temperature cycle (based on Coenen (2011) and Waterhouse et al. (2012))

- Thus the cabin temperature should be between 16-18˚, stimulating sleep, helping passengers to stay asleep and to adopt a new circadian rhythm for a new time zone (see also 1.1.1). In a study by Pang, Qin, Liu, and Liu (2014) on seven intercontinental flights, cabin temperatures ranged between 20-27˚C during cruise time. Cui, Ouyang, and Zhu (2014) found similar results ranging between 22.1-27.6˚C for ten domestic flights. Meaning most cabins are slightly too warm for a good sleep. As stated by Bouwens (2017), the cabin climate conditions can only work when passengers are offered sufficient means for creating their own comfort (de Korte et al., 2015; Kuijer & De Jong, 2012). Enabling passengers to control their own (local) temperature within their seat may benefit the comfort experience (Luo et al., 2016; Pasut, Zhang, Arens, Kaam, & Zhai, 2013; Vink, 2014a; Williams & Irurita, 2005).

5.3.2 Cool head

Cooling takes place mainly through the head and the face and in less extent through the hands and feet. Therefore having a cool head significantly enhances nighttime sleep and has a positive effect on objectively measured deep sleep (Coenen, 2006; Law, 2013). In a small study (n=5) Kawabata and Tokura (1996) compared the effects of a cool and normal pillow, where the cool pillow was regarded subjectively as better for deep sleep by the subjects. Thus a cool headrest may benefit sleep. Further research is advised on the effects of a cool headrest on sleep and the benefits of implementation in aircraft seats.

5.3.3 Microclimate

In contrast to head cooling, hands and feet should be warm to dilate the blood vessels, helping the body to cool down and promote sleep. Literature is inconsistent here, but the microclimate below the blanket should be within a thermal neutral zone of 20 to 32°C (see Table 5.2), which is the air temperature where the skin temperature will not change (Coenen, 2006; Z. Lin & Deng, 2008). When the temperature gets higher, the body will sweat to lose warmth resulting in too high humidity and consequent sleeping disturbances (Coenen, 2006). When the temperature gets too low, the body will shiver to warm which requires energy of the body and may result in muscle stiffness and sleeping disorders (Coenen, 2006; Haskell, Palca, Walker, Berger, & Heller, 1981).

Women have a preference for a warmer microclimate than men (Coenen, 2006; Haex, 2005). Passive body heating before sleep (40-43˚ for 30-90 min in e.g. a bath, resulting in a central body temperature increase of 1.4-2.6 ˚C) has a positive effect on sleep for healthy young and sleep-disturbed older adults (Kräuchi et al., 1997), as it shortens sleep onset latency and increases the duration of deep sleep (S3+4).

Thus active microclimate management – based on gender, time and personal preference – within the seat can improve sleep quality and thus comfort.

Table 5.2 | Overview of studies stating thermal neutral (TN) zone temperature ranges (based on Z. Lin and Deng (2008) and Flynn-Evans, Caddick, Gregory, and Center (2016)). For full table, see Appendix J.

Source	Thermal neutral zone
Macpherson (1973)	29-32˚C
Karacan, Thornby, Anch, Williams, and Perkins (1978)	22.2˚C
Haskell et al. (1981)	29˚C
Vokac and Hjeltnes (1981)	34-36˚C
Candas, Libert, and Muzet (1982)	32˚C
Candas, Libert, Vogt, Ehrhart, and Muzet (1979) (as cited by Muzet et al. (1984))	28.6-30.9˚C
Palca, Walker, and Berger (1986)	29˚C
Sewitch, Kittrell, Kupfer, Reynolds (1986)	20-22˚C
Di Nisi, Ehrhart, Galeou, and Libert (1989)	30˚C
Goldsmith and Hampton (1968)	34-36˚C
Okamoto, Mizuno, and Okudaira (1997)	26-32˚C
Dewasmes, Telliez, and Muzet (2000)	28˚C
Coenen (2006)	27-29˚C
Z. Lin and Deng (2008)	28-32˚C
Okamoto-Mizuno and Mizuno (2012)	29˚C
Kingma, Frijns, Schellen, and van Marken Lichtenbelt (2014)	27.9-28.5˚C
Kingma et al. (2014)	14.8-24.5˚C
Lan, Pan, Lian, Huang, and Lin (2014)	26˚C

5.3.4 Minimising jetlag symptoms

When travelling to another time zone, our circadian rhythms do not correspond to the local time and conditions. This results in a 'jetlag', what is experienced as unpleasant drowsiness, tiredness and confusion, leading to subjective discomfort and fatigue due to disturbed sleep, impaired alertness and gastrointestinal disturbance (Coenen, 2011; Drake & Wright, 2011; Zee & Goldstein, 2010). Also, disturbed and shortened sleep before and/or during travel may contribute to these symptoms (Drake & Wright, 2011). Adjusting to a new time zone requires a few days (and in some cases weeks), as the human body requires a day for each hour of time shift in the circadian rhythm (Coenen, 2006; Onen et al., 1994).

Promoting sleep or wakefulness during sleep in flight – and pre-flight circadian adaption – may shorten the duration of jetlag symptoms in the new time zone. When travelling eastwards, it is recommended to sleep during that flight. As most eastward flights are at night, they provide more opportunity. Earplugs, noise-cancelling headphones, eyeshades and adjustment of cabin lighting and temperature may help promote sleep. When travelling westwards, postponing sleep until bedtime of the new time zone is advised. Naps during flight and in the new time zone may be effective in promoting subsequent wakefulness, although napping will influence the ability to fall asleep. Again, cabin lighting and temperature can be helpful in the time zone adjustment (Drake & Wright, 2011; Zee & Goldstein, 2010). Also controlling light and (micro-climate) temperature within the seat design may contribute to time zone adjustment and minimising jetlag symptoms.

5.4 Influence of stimulus on sleep

In an aircraft one experiences sound of the engines, sound, movement and light of other passengers and crew, and may be disturbed by (safety) lights, a cold or warm cabin and dry cabin air. This all has a negative impact on sleeping performance. When one sleeps, the environment should be minimal in stimuli. For instance noise pressure levels and high frequency sounds should be reduced to improve the passenger comfort experience (Pennig, Quehl, & Rolny, 2012) and light can both respite sleep as initiate sleep (Zee & Goldstein, 2010) (as there is also potential to make use of light to reduce jetlag symptoms, see §1.1.1).

Due to our natural sleep-defence mechanisms in the brain we wake up by strong stimuli such as sound, light and touch. Our sleep-defense mechanism can also wake us up based on weak stimuli, such as a burning smell, mumbling or sudden silence. Normal occurring sounds (e.g. soft ticking clock, humming fan) of which we are used to will not disturb sleep at al, unless we get annoyed by them (e.g. creaky bed). Then the stimuli will be negatively interpreted and therefore becomes relevant, which has consequences for the sleep (Coenen, 2006; Drake & Wright, 2011; Flynn-Evans et al., 2016).

In the aircraft these strange stimuli will mostly come from the aircraft (e.g. vibrations, noise, roll and pitch movements), cabin crew (e.g. trolleys through the aisle, service preparation in the galley, smell of food and drinks) and fellow passengers (e.g. coughing, snoring, talking, movement, touch, smell). Also the lack of privacy on board and sleeping in a strange environment may not benefit sleep. It is therefore desirable to minimise sudden stimuli in the aircraft seat. This can be prevention of disturbance by FA's or other passengers, limitation of light pollution, etc.

Background noise like engine sounds masks other (more disturbing) sounds (Pierrette, Parizet, Chevret, & Chatillon, 2015; Shafiquzzaman Khan, 2003). Thus it might be better to mask (sudden) cabin sounds caused by crew, passengers (e.g. talking, coughing) and their equipment (e.g. trolleys, electronic devices), than aiming to completely silence the cabin (Bouwens, 2017). For example, BCP's complain about the lack of cabin noise in the BCP cabin up front in the new Boeing 787 Dreamliner, making their conversations less private than they were used to Schultheis (2016a). However, Basner, Glatz, Griefahn, Penzel, and Samel (2008) and Schmidt et al. (2013) show that aircraft noises cause poorer sleep quality. Thus, limiting cabin noise is still relevant.

5.5 Sleeping posture and movement

Humans – with a few exceptions there – prefer sleeping on a flat surface, preferably with some support (e.g. bedding system) (Coenen, 2011; Haex, 2005). During sleep we also optimise our body posture in order to unload the vertebral column (e.g. for rehydrating the intervertebral disks) (Haex, 2005), which is one of our most vital and at the same time vulnerable human organs, which needs to be protected (Gracovetsky & Farfan, 1986). Our sleeping posture may also be related to our sleep quality, as stated by De Koninck, Gagnon, and Lallier (1983).

5.5.1 In sleep movement

We do not sleep in fixed postures, but often have a preferred one which is dominant (Coenen, 2006; Coenen & Kolff, 2011; Haex, 2005). In this posture people mostly fall asleep, but will move as healthy sleep requires several major posture changes throughout the night (Coenen, 2006; de Koninck, Lorrain, & Gagnon, 1992; Verhaert, 2011). Movement in bed is of importance to prevent pressure sores (Defloor, 2000; Rithalia, 2005), muscle stiffness (Haex, 2005) and for proper blood flow (Defloor, 2000). At an average night, a person will change posture between 20-40 times (Coenen, 2006; Coenen & Kolff, 2011; de Koninck et al., 1992; Haex, 2005; H. Johnson, Swan, & Weigand, 1930; Verhaert, Haex, De Wilde, et al., 2011). See
Table 5.3 for a comparison.

5.5.2 In sleep posture

In literature, three main postures are defined: lateral, supine and prone. Within these there are many variations (see Figure 5.5), but these are not widely studied. Some studies make a differentiation between left and right lateral sleeping. Only de Koninck et al. (1992) gives a more elaborative analysis of the posture, describing the position of the head, trunk, legs and arms.

Literature indicates that lateral and supine sleeping postures are mostly taken (see Table 5.4), with roughly 60-70% lateral, 20-30% supine and 5-10% prone. Postures taken during sleep in studies of de Koninck et al. (1992), Gordon, Grimmer, and Trott (2004) and Gordon and Buettner (2009) based on video analysis, ranged for lateral between 64,5-73%, for supine 11.2-21.0% and for prone 0.5-15.2%. Sensor based studies of Verhaert, Haex, De Wilde, et al. (2011), Coenen and Kolff (2011) and Kaplowitz et al. (2015) found 39.1-60% for lateral, 30.2-55.3% for supine and 5.6-13.6% for supine. Survey based studies on self reported sleeping posture of Gordon, Grimmer, and Trott (2007), Kim, Jeoung, Park, Kim, and Ritch (2014) and Kaplowitz et al. (2015) report for lateral 45.5-78%, supine 11.2-25.1% and prone 2.7-6%. In a survey (n=247) by McCabe and Xue (2010) 50% of the men and 73% of the women preferred lateral sleeping, indicating gender differences. However, Gordon et al. (2007) found no significant difference in lateral sleeping and gender, but reports that females are significant less likely to report supine sleeping position than males.

Considering the usability of survey based dominant posture determination, Gordon et al. (2004) found that 92% of the subjects predicted their dominant 'usual' sleeping posture correctly. In the study of Kaplowitz et al. (2015) primary sleep position matched the self-reported posture in 77% of participants. Verhaert, Haex, De Wilde, et al. (2011) found 67% of the subjects correctly judged their dominant sleep posture and 93.7% spent more than 50% of time in bed in their dominant sleep posture. However, Verhaert, Haex, De Wilde, et al. (2011) also showed in the same study that subjects also spend a significant amount of time in other (non dominant) postures, as only 43.7% of subjects spent more than 60% of the time in their dominant posture.

In literature supine and lateral sleeping are generally considered as the 'best' positions (Coenen, 2006; Haex, 2005), 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 as in business class, prone sleeping in a reclined seat is unpractical – never the less impossible. Therefore this posture can be neglected in a PEC seat. There is no difference in loading on the body for left or right side sleeping, except when sleeping on the left side the weight of the liver works on the lungs and stomach (Haex, 2005). When looking at the data stated in Table 5.4, in some studies there is a significant preference for left or right side sleeping, where others show none. Besides the lac of a clear preference, literature also suggests limiting sleep to one side is not advisable, as movement in sleep is natural and essential to prevent pressure sores (Farine & Seaward, 2007) (see also §5.5.1).

Table 5.3 | Posture change and movement per night

Source	Sample size	Posture change	Movement
de Koninck et al. (1992)	n=10 (18-24y)	19.6 ± 5.6	n.a.
	n=10 (35-45y)	27.1 ± 8.9	n.a.
Coenen and Kolff (2011)	n=28 (23-80y)	14.1 ± 7.1	n.a.
Verhaert, Haex, De Wilde, et al. (2011)	n=15 (26.1 ± 8.8y)	15.7 ± 8.7	75.0 ± 33.3

Figure 5.5 | Sleeping postures

Table 5.4 | Time spend in each sleeping posture or preferred/dominant sleeping posture

<table>
<tr><th rowspan="2">Source</th><th rowspan="2">Process</th><th rowspan="2">Sample size</th><th colspan="2">Lateral</th><th rowspan="2">Supine</th><th rowspan="2">Prone</th></tr>
<tr><th>Left</th><th>Right</th></tr>
<tr><td>de Koninck et al. (1992)</td><td>Video analysis</td><td>n=20 [1]</td><td>30.7 ± 10.9%</td><td>33.8 ± 12.2%</td><td>20.1 ± 12.8%</td><td>15.2 ± 16.0%</td></tr>
<tr><td>Gordon et al. (2004)</td><td>Video analysis</td><td>n=12</td><td colspan="2">73.0 ± 18.0% [2]</td><td>21.0 ± 14.6% [2]</td><td>0.5 ± 8.0% [2]</td></tr>
<tr><td>Haex (2005)</td><td>Based on international data obtained in collaboration with a mattress company [3]</td><td>Unknown [3]</td><td colspan="2">65%</td><td>30%</td><td>5%</td></tr>
<tr><td>Gordon et al. (2007)</td><td>Survey of self reported posture of sleep</td><td>n=812 [4]</td><td colspan="2">72.0%</td><td>11.2%</td><td>4.9%</td></tr>
<tr><td>Gordon and Buettner (2009)</td><td>Video analysis</td><td>n=12 [5]</td><td>42.1 ± 18.0 %</td><td>29.8 ± 20.4 %</td><td>21.7 ± 13.0%</td><td>6.4 ± 7.4%</td></tr>
<tr><td>Verhaert, Haex, De Wilde, et al. (2011)</td><td>Mattress indentation measurement</td><td>n=15</td><td>30.2 ± 16.8%</td><td>26.0 ± 17.2 %</td><td>30.2 ± 20.5%</td><td>13.6 ± 16.4%</td></tr>
<tr><td>Coenen and Kolff (2011)</td><td>Sensor monitoring (Pro-tech Embla) on subject body</td><td>n=28</td><td>21.8 ± 26.2%</td><td>17.3 ± 21.1%</td><td>55.3 ± 15.8%</td><td>5.6%</td></tr>
<tr><td rowspan="2">Kim et al. (2014)</td><td rowspan="2">Survey of preferred sleeping posture of open-angle glaucoma patients</td><td rowspan="2">n=1384[6]</td><td colspan="2">17.5%[8]</td><td rowspan="2">25.1%</td><td rowspan="2">2.7%</td></tr>
<tr><td>13.7%</td><td>14.3%</td></tr>
<tr><td rowspan="3">Kaplowitz et al. (2015)</td><td>Sensor monitoring (Embletta X10) on subject body</td><td>n=29</td><td>23%</td><td>37%</td><td>32%</td><td>8%</td></tr>
<tr><td rowspan="2">Survey of self reported posture of sleep of open-angle glaucoma patients</td><td rowspan="2">n=178 [7]</td><td colspan="2">19% [8]</td><td rowspan="2">16%</td><td rowspan="2">6%</td></tr>
<tr><td>26%</td><td>33%</td></tr>
</table>

1 Age groups 18-24 and 35-45 are combined, as these ages are more likely to fly in premium cabins frequently.
2 Based on reanalysis of dataset, as table 2 of Gordon et al. (2004) contains mistakes. Remaining percentage is 'other'.
3 Approach, sample size and sample diversity could not be shared due to NDA (personal communication with Haex (2017)) and thus scientific ground is thereby unverifiable.
4 Males and females are combined. Remaining percentage is 'other'.
5 All age groups.
6 Based on reanalysis, combining open-angle, normal-tension and high-tension Glaucoma patient groups. Remaining percentage was no preferred lying position.
7 Includes n=29 subjects from posture monitoring study.
8 Subjects stating having no preference between right and left lateral sleeping.

5.6 Bedding system

During the day we mentally and physically exhaust our body, whereas the body recovers during sleep (as discussed in §5.2). Facilitating a proper sleep system within the aircraft is thus essential, as it has to support the human body in a way that it allows muscles to recover and intervertebral discs to rehydrate from nearly continuous burdening by day (Dreischarf, Shirazi-Adl, Arjmand, Rohlmann, & Schmidt, 2016; Haex, 2005; Verhaert, Haex, Wilde, et al., 2011). This can be achieved by supporting the body with a mattress and a pillow so that the spine is in its natural physiological shape (Haex, 2005; Verhaert, Haex, Wilde, et al., 2011). The sleep system should also account for proper temperature isolation and breathability (moisture management), e.g. by a blanked and mattress.

5.6.1 Mattress

The mattress takes an important role in the support of the human body while sleeping. Multiple studies have found relations between the mattress and sleep comfort and quality (Enck, Walten, & Traue, 1999), but remain vague on the actual mattress properties making compare and interpreted results difficult (Verhaert, Haex, Wilde, et al., 2011). Especially the firmness and suspension are of importance, since a coronal straight spine enhances resting and minimises back pain (Coenen, 2006; Haex, 2005; Mannekens, 1996).

The mattress, support frame and pillow of the sleep system should thus account for body contours and weight distribution, providing minimal strain on the muscles and spine. When sleeping lateral, especially the shoulder but also the hip should have to sink into the mattress to keep a straight back (projected in the frontal plane) with a pillow used to keep the head horizontal while maintaining a natural S-curve of the spine; cervical lordosis, thoracic kyphosis and lumbar lordosis (Coenen, 2006; Haex, 2017; Van Deun et al., 2012). When having a big waist, more support is needed to prevent sagging (Haex, 2005; Van Deun et al., 2012). The same counts for sleeping supine, where more support is needed for the more heavy parts of the body such as the hip (preventing pelvic canting and lumbar flattening) to keep the spine into its natural S-curve (Haex, 2005).

Anthropometric aspects such as body contours (shoulder, waist and hip width) and weight distribution are highly individual as can be seen in Figure 5.6. This is especially important in the internationally diverse context of flying. Haex (2005), Coenen (2006) and Van Deun et al. (2012) suggest a bedding system should be allocated specific to the person. Also the taken posture influences the body contour and the required support. As minor and major posture changes occur in natural sleep (see §5.5.1), an ideal bedding system within the aircraft facilitates and/or adapts to support the changed loading posture and person specific (Haex, 2005; Verhaert, Haex, Wilde, et al., 2011). It is however important to give the passenger control of this feature, as automated adjustment without the user's consent (e.g. by pushing a button) will be experienced as uncomfortable (Vink, 2014a).

5.6.2 Conflict between seat and sleep support

Not only does the mattress/padding in a premium aircraft seat have to support the difference between lying lateral and supine during sleeping, it should also support upright seating activities. When the aircraft seat is in an upright sitting position, in the pelvis region most support (firmness) is needed (Hartung, 2006; Raphael Zenk, 2008; R Zenk, Franz, Bubb, & Vink, 2012). When translating from a seat to a bed, that same area at the pelvis and the shoulder area should become soft for lateral sleeping to allow a straight alignment of the spine (see Figure 5.7 for a comparison). This transition from firm to soft may also increase the experienced comfort and softness of the bed (S. van Veen & Vink, 2016; Vink, 2014c). When sleeping supine, again more support is needed at the pelvis and chest area. Adaptability of firmness per area should thus be considered for a bed-seat, to properly support all required postures. Knowledge on this matter is however limited and further research is needed.

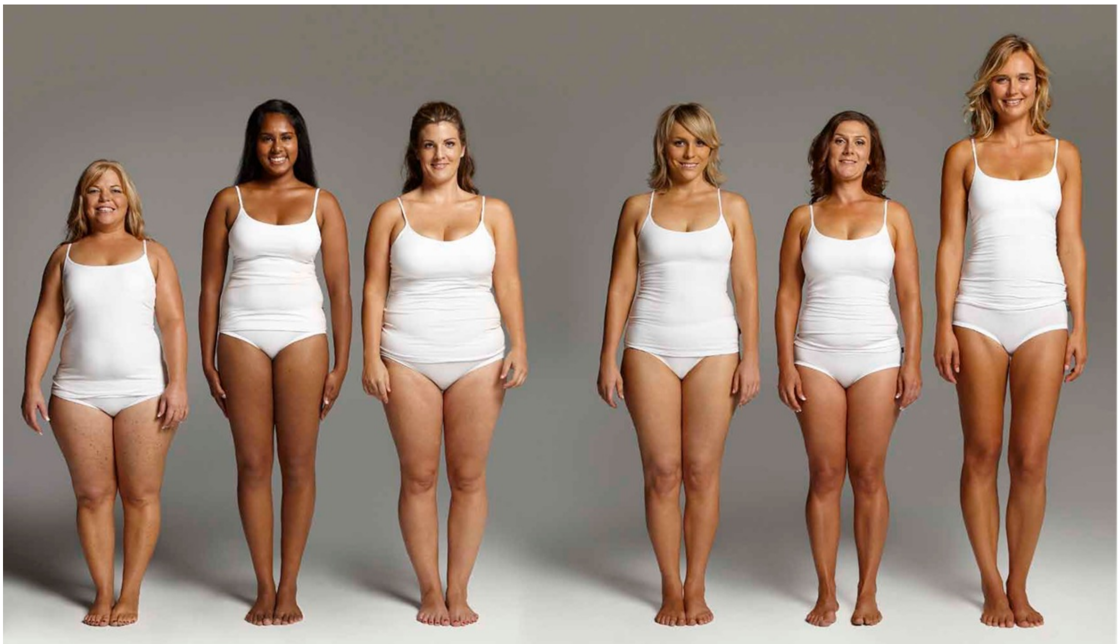


Figure 5.6 | These women show different anthropometrics while weighing the same (from Adams (2012) and Goossens (2016))

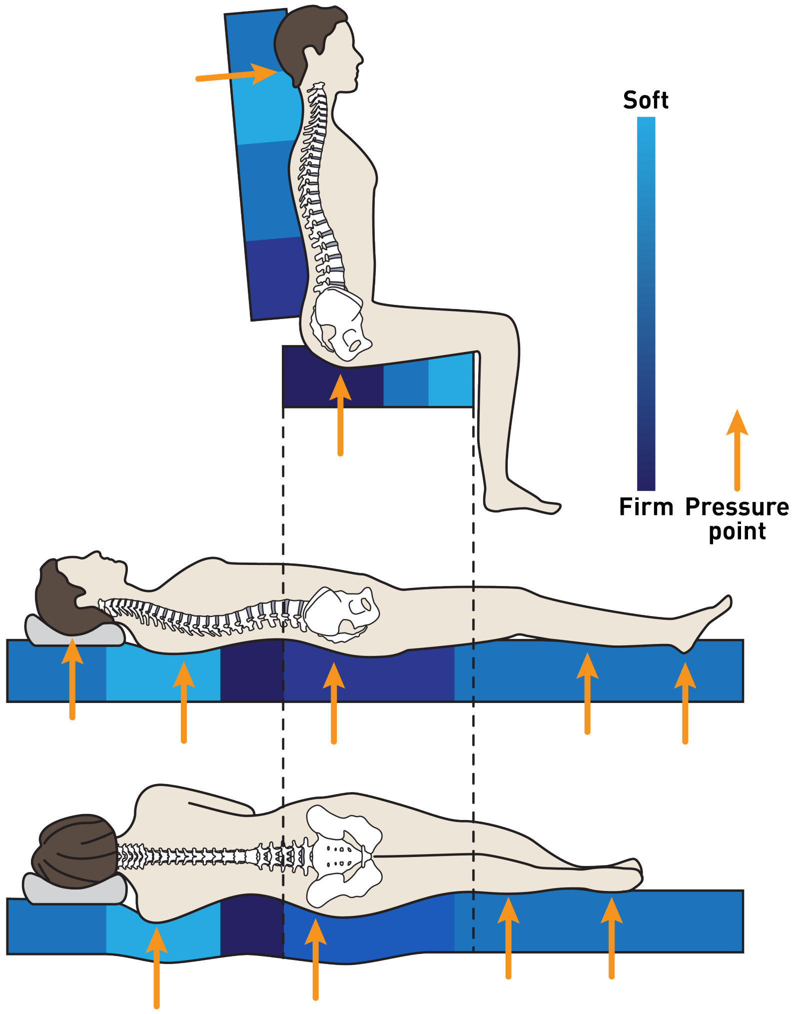


Figure 5.7 | Pressure points and advised pressure distribution for upright, lateral and supine sleeping. Where in upright seating the pelvis area has to carry the biggest load and thus should be firm, in sleeping this area needs to be soft to allow the pelvis to sink in. Based on Agrawal and Chauhan (2012), Hartung (2006), R Zenk et al. (2012), Raphael Zenk (2008), Haex (2005) and Vink and Lips (2017).

5.6.3 Pillow

Together with the mattress, the pillow supports the body during sleep; and more specifically the head. The heavy head needs to be supported minimising strain on muscles and the intervertebral disks, as no support will make the head incline downward causing the spine to curve (Coenen, 2006; Haex, 2005; Verhaert, 2011; Yim, 2015). The challenge is the transition from the mattress towards the pillow for different postures, as adequate height of the pillow is important to comfort and minimise muscle activity (Sacco et al., 2015). When sleeping lateral the head needs higher support than when sleeping supine, due to the head its anthropometrics (Coenen, 2006; Haex, 2005; Verhaert, 2011). This might also be the reason why people tend to put their hands below their pillow, raising their head when lacking sufficient height support from the pillow. As movement during sleep is essential (see §5.5.1), it is important that passengers are given the freedom to move the pillow or headrest in their aircraft seat, as they would at home. Persson and Moritz (1998) stated that the ideal pillow should be soft and not too high, should provide neck support and should be allergy-tested and washable. Yim (2015) states a soft and not too high pillow with firm support for cervical lordosis appears to be the optimal type of pillow. As stated in §4.5, not all passengers like neck support. Therefore it is advised to offer passengers a choice in pillow type or the possibility to adjust neck support in a headrest.

5.7 Current conditions in PEC and BC

In business class and premium economy there is a multitude of seat inclinations offered. The so-called cradle seats offer a 150-160˚ recline, angled lie flat seats 170˚ and full flat seats 180˚, where in long-haul economy class 103-122˚ are common. These inclinations have a strong relationship with the quality of sleep and sleeping comfort. For example business class passengers complain about non-full flat seats as they are slowly sliding down out of their seat. Thus considering the right inclination and support within the aircraft seat is important.

5.7.1 Full flat sleeping: why lying when sleeping is better and preferred

"The highest level of comfort during the day is reached when lying in bed with the activity of sleeping"

Vink (2014b)

Although many people may get a reasonable sleep in a comfortable chair, lying flat in a bed is still the most comfortable way of sleeping (Aeschbach, Cajochen, Tobler, Dijk, & Borbély, 1994; Coenen, 2006). A lying posture requires less energy, allowing maximal (muscle) relaxation (Nachemson & Elfstrom, 1970), the pressure on the spine and joints is the lowest (Nachemson & Elfstrom, 1970; Polga et al., 2004; Sato, Kikuchi, & Yonezawa, 1999; Wilke, Neef, Caimi, Hoogland, & Claes, 1999) – allowing intervertebral disks to rehydrate – and the heart has the least effort to pump blood through the body (Coenen, 2006; Haex, 2005). A postural change from upright or sitting to a supine position is associated with a nocturnal increase in skin temperature and a declining body core temperature which amplifies day-night difference, bringing people into sleep (Kräuchi et al., 1997; Marotte & Timbal, 1981; Tikuisis & Ducharme, 1996). Lying flat also causes minimal obstruction for posture change and micro-movements during sleep, allowing proper blood flow and preventing bedsores (Haex, 2005). Although full-flat sleeping is possible in BC, PEC only offers limited recline.

In a study by Balkin, O'Donnell, Kamimori, Redmond, and Belenky (1989) (n=45) on daytime sleep of 6 hours in a chair in a well-lit and crowded room after sleep deprivation (placebo only), sleep efficiency (%TST of TIB) was only 71.5% with only 39 minutes of slow wave sleep (SWS, stage 3+4 deep sleep). In a comparable study by Dijk, Brunner, and Borbély (1991) (n=8) on recovery sleep in the morning of 7,6 hours in a bed, sleep efficiency was 94%, with 127 min. of deep sleep. Aeschbach et al. (1994) compared sleeping in a bed with sleeping in an economy aircraft seat with a reclined backrest and ample leg roomwhile having the seat belt on in an almost dark room (comparable to PEC) with eight subjects (n=8). Sleep in a bed had a sleep efficiency of 91.7% versus 79.2% in the aircraft seat

(P < 0.01), 101 min. vs. 77.6 SWS (no sig.) and 91 min. vs. 51 min. REM sleep (P < 0.01). Subjective sleep was also rated sig. lower for seated sleeping by the subjects. This shows that the upright sleeping severely influences the quality of sleep.

In a study by Hayashi and Abe (2008) on short napping between driving sessions in a car seat, backrest reclined of 130˚ and 150˚ incline reduced subjective sleepiness, improved task performance and suppressed and suppressed drowsiness in the following driving sessions, where napping with a 150˚ backrest angle had better results over 130˚. Nicholson and Stone (1987) shows similar results in their comparison of three seats and a bed with different reclines (see Table 5.5 for a comparison). The seat with 139.5˚ recline had similar results to a bed, where in the 127˚ reclined seat sleep was reduced and the amount of awake activity was increased. In the 127˚ recline sleep was worse, as sleep time was shorter, had more awakening activity and sleep efficiency reduced. The same study therefore states that a 130˚ (40˚) backrest angle should be minimal for adequate sleeping. Also FAA regulations on Class 3 crew rests with sleeping capabilities (composed in 1994 (U.S. Department of Transportation Federal Aviation Administration, 2012)) require a minimal backrest inclination of 130˚ (40˚) (U.S. Department of Transportation Federal Aviation Administration, 2013). Also reports like Simons and Spencer (2007) refer to Nicholson and Stone (1987), but a larger study sample and more recent studies are lacking to support this claim.

This indicates that the flatter the seat/bed surface, the better we sleep. Our vestibular (responsible for the sense of balance), located in out ears, are used to a horizontal (or flat) orientation when sleeping. The hypothesis is that people fall asleep easier and sleep better when experience a flat – or close to flat – sleep orientation with their head.

5.7.2 Upright sleeping: the challenge of the 'falling motion reflex'

Although full flat sleeping is preferable, it is not possible in PEC due to space constraints. PEC however offers a better recline than in EC, allowing a better sleep. However, upright or reclined sleeping poses some extra challenges considering the head, gravity and muscle relaxation. During SWS and REM muscle tone is lost (see Table 5.1), making it hard to keep sitting upright (Coenen, 2006; Dijk, 2009). Depending on the posture, gravity will make the head or upper body slide/fall forward or sideways due to the lack of counteraction by the muscles and the lack of support. The hypothesis is that this sense of falling caused by losing muscle tension, will automatically trigger the sleep-wake system (see §5.4), makeing the passengers wake up; a *'falling motion reflex'*. Due to this, passengers are napping (staying in S1 and S2) but never reach deep sleep (S3+4) or REM, resulting in no effective sleep and thus feel less refreshed and comfortable. A new PEC headrest design could prevent this '*falling motion reflex'* trough proper support, improving the sleep quality of PECP's and thus the flight experience (see §8.1.2 for an ecample).

Table 5.5 | Effect of different sleep inclinations (deg) on duration of sleep stages (min.). TST=Total Sleep Time, the total time spend in NREM and REM. SE=Sleep Efficiency, the time spend effectivily sleeping (NREM+REM) of Total Bed Time (TBT).

Source	Sample size	Backrest inclination	TST	SE	Awake	Stage 1	Stage 2	SWS (stage3+4)	REM
Nicholson and Stone (1987)	n=9	**180˚**	436.5	**90%**	13.9	37.8	268.6	36.9	94.4
		139.5˚	425.1	**89%**	23.6	33.4	267.0	30.6	94.4
		127˚	405.7	**86%**	33.1	35.3	253.8	35.9	80.4
		107.5˚	355.0*	**77%****	52.5*	45.3	213.6**	42.0	56.6*
Aeschbach et al. (1994)	n=8	**180˚**	440.2	**91.7%**	39.8 [1]	31.5	216.5	100.9	91.3
		120˚ [2]	380.0**	**79.2%****	99.8 [1]	69.6*	181.9	77.6	50.8**
Hayashi and Abe (2008)	n=11	**150˚**	14.9	**82%**	3.2	6.6 **	8.3 ***	0.0	0.0
		130˚	14.9	**70%**	6.4	10.2	4.7	0.0	0.0

[1] Calculated. Not given in study.

[2] Angle was not given by study, so an assumption was made. The seats of this study were economy class seats from a commercial airline and were put in a reclining position. A 15˚ recline on top of a 105˚ angled backrest was chosen for this comparison based on common economy class seats of today.

* P < 0.05 within same study

** P < 0.01 within same study

*** P < 0.001 within same study

5.8 Conclusion

The first stage of sleep (S1) is critical, as the shorter it is, the deeper the sleep will be. As it is relative easy to get woken out of S1, a seat that minimises external stimuli is desirable (such as light, sound, temperature and disturbances by cabin services), as it helps passengers to get and keep asleep better. Facilitating deep sleep (S3+4) and REM are important to the quality of sleep, as in these stages the body and mind recover. It is thus essential to promote and allow passengers to reach these stages within their seat. Monitoring sleep stages can be used for waking passengers at the end of REM, to make them feel less disoriented and more rested.

Controlling temperature and light within the seat and cabin can promote sleep, help keeping asleep and improve sleep efficiency, improving passenger comfort experience as they land more refreshed. Slowly dimming the light with warm colours and cooling the cabin can be used to promote sleep, where increasing light intensity with cold colours and warming up the cabin can be used for waking up naturally. Also a cool headrest/pillow can promote deep sleep, might be interesting to implement in a headrest. It might also be interesting to manage the microclimate temperature to control sleep and improve sleep quality (e.g. increase body core temperature when falling asleep, keep a steady neutral temperature during sleep and warm up or cool down when waking up). Such in seat and cabin systems can also help the passenger to (pre) adjust to the new time zone, which can improve the travel experience and making time on the ground at the destination more effective. This is especially interesting for BCP's who have to start working right away at their destination.

The challenge her is that passengers have different anthropometrics and the required support for different activities and postures are different (e.g. seat vs. bed, lateral vs. supine); areas in the mattress that need to be soft and hard differ for the sleeping and IFE positions. Firmness adjustment per region based on pressure sensor input (determining ideal pressure distribution based on posture and weight) may be a solution. In addition, offering passengers choice in mattress firmness and pillow firmness and shape can improve the sleep quality (e.g. firmer for Asia, softer for USA), so passengers sleep under more familiar conditions. Also allowing sufficient freedom of movement with minimal resistance is required, as movement and postural change is essential for qualitative sleep and preventing bedsores.

Full flat bed sleeping facilitates the most qualitative sleep and is thus sufficient in BC. The challenge for premium economy is the limited recline, as muscles relax when entering deep sleep (S3+4) and when in REM, making it hard to keep the head upright. Movement of the head by gravity may triggering the'falling motion reflex', waking up the passenger. Where full flat sleep minimises resistance and thus allowing essential in bed movement, in upright sleeping movement capability is more restricted. A headrest which prevents triggering the 'falling motion reflex', but allows natural in sleep movement and postural change (prone and lateral) may be beneficial to the sleepability and quality of sleep with limited recline.

5.8.1 Sleep design challenges in business class

- Difficulty to fall asleep and stay asleep due to disturbing factors (e.g. sound, light, temperature).
- Necessary sleep cycle vs. flight (service) regime.
- Current sleep-rhythm vs. destination time.
- Everybody needs a personalised mattress (anthropometrically).
- Conflict between lateral and supine sleeping and sitting support, requiring posture dependent and activity dependent support.

5.8.2 Sleep design challenges in premium economy

- Preventing falling motion effect in reclined position.
- Facilitate movement while sleeping reclined.

5.8.3 Recommendation for further research and development

Research on sleep medicine is extensive, however research on bed ergonomics and comfort is young and limited. Further research on personalisation of mattress support, posture specific support and (especially) upright sleeping support is advised.

5.9 Further reading

For further reading on sleeping ergonomics and comfort, Haex (2005) *Back and bed: Ergonomic aspects of sleeping* is highly recommended, as it is the most comprehensive work to date on this topic. For further reading on sleep, sleep medicine and sleep research techniques, Kryger et al. (2016) *Principles and Practice of sleep medicine* and Lee-Chiong (2010) *Best of sleep medicine* are recommended. For further reading on improving initiating and maintaining sleep, the graduation thesis of Van der Heijden (2016) *A non-pharmacological and scientifically proven solution for people suffering from insomnia* is recommended. For further reading on sleeping within air- and spacecraft's Flynn-Evans et al. (2016) *Sleep Environment Recommendations for Future Spaceflight Vehicles* and Simons and Spencer (2007) *Extension of flying duty period by in-flight relief* are recommended. Also the work of van Meurs (2017) may be interesting.

5.10 Recommendations for seat manufacturers and airlines

The consideration, exploration and/or implementation of the following recommendations (based on e.g. Flynn-Evans et al. (2016), Coenen (2006), Simons and Spencer (2007) and insights of the author) are advised:

Spatial design cabin

- Sleep stations (seats) should be located away from common areas such as the galley as much as possible.
- Lavatories should be near sleep stations (for easy visit), but should be separated by a distance sufficient to minimise noise from the waste management systems (e.g. door and suction noise) and disturbances by other passengers.
- Space for storing personal items should be accommodated in seat.
- Adjustment and customisation of the sleep environment should be allowed to meet personal preferences.
- Minimise cabin and service disturbances. Belt checks should be conducted without disturbing sleeping passengers (e.g. electronical check) and cabin services should be postponed for passengers who do not want to make use of it.

Sensorial/disturbing factors

- Complete darkness is optimal for sleep. Sleeping quarters should be able to be darkened as much as possible. However, some (red) aisle lighting is required for crew and passengers and sufficient light for quick orientation within the seat.
- Eye masks should be available to passengers. This is common practice through amenity kits in premium cabins.
- Light pollution from other areas (e.g. galleys, lavatories and the aisle) should as minimal as possible. Red light can be an option here.
- Indicator lights (e.g. personal light switch) should be used only where necessary and should be dim and red.
- Mimicking sunrise/sunset with cabin lights may be desirable to improve sleep latency and in preparation of time zone adjustment (minimising jetlag symptoms).
- All forms of noise should be below 35 dB in sleeping quarters (if possible).
- Familiar noise, such as human voices, is disruptive to sleep at lower decibels, so noise mitigations to protect against noise pollution from common areas is important.
- Intermittent noise is more disruptive to sleep than continuous noise and should not vary by more than 5 dB from background noise.
- Continuous (white/engine) noise of < 25 dB may be useful to protect sleep by buffering other noises. This can be done within the seat (e.g. played at the head end of the bed), but should be controlled by the passenger.
- Earplugs and noise-cancelling headphones should be made available to passengers. This is common practice in premium cabins.
- The depth of sleep and individual differences predict arousal from auditory alarms. Multi-sensory wake-up alarms (e.g. by light, sound, temperature and vibration) may be desirable.

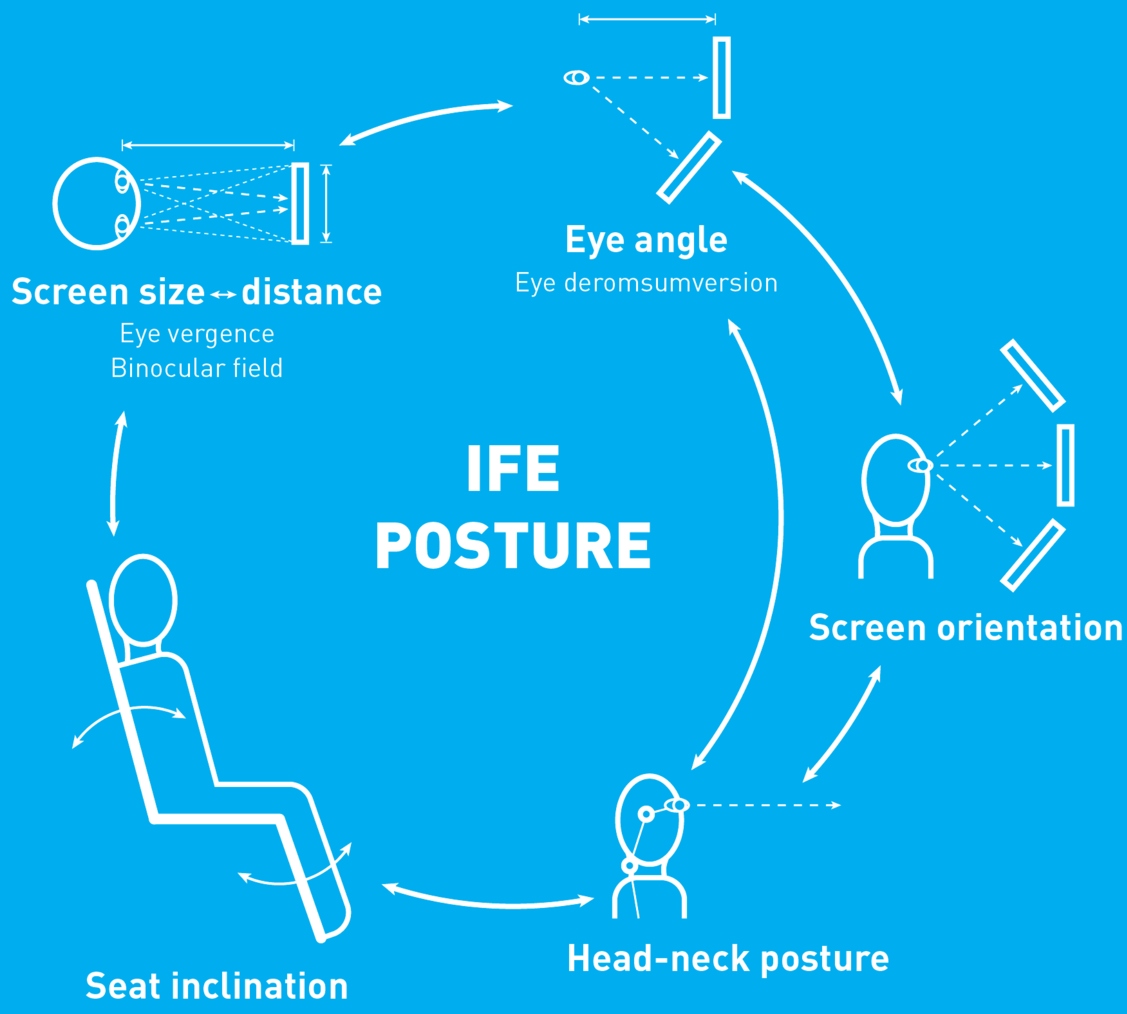
Environmental factors (temperature)

- Ambient temperature should be maintained between 18.3-22˚C during sleep (assuming adequate bedding (e.g. blanket and pyjama) is available, cooler is better (16-18°C). When no insulation is available, hotter temperatures are required). ▸

- Humidity should be between 45-60% relative to ambient temperature.
- Sufficient fresh air for oxygen inhalation and carbonic exhalation.
- Passenger should have control of (in seat) microclimate temperature within the normal range in order to account for individual and gender preferences (as women tend to like a warmer temperature than men).
- Sufficient bedding should be provided to allow passengers to achieve a microclimate 25-35°C. Bedding should be modifiable, so that passengers can add or remove insulation based on individual preferences.
- Providing socks or local heating sources to allow for the warming of proximal and distal skin temperature during sleep may facilitate sleep onset.
- A cool headrest/pillow can promote deep sleep.

Spatial design seat for sleep

- Allow for a horizontal positioning on a flat surface as much as possible. A minimal backrest recline of 130° (40°) should be considered for proper sleep (although further research is advised here).
- Seat/bed dimensions should accommodate movement during sleep and changes in body position. A bed 200mm longer than the tallest bed user and have a width between 800-900mm is recommended.
- Feet space is important to allow movement and postural change. The limited compartments for the feet of some current BC seats make it difficult to position feet side by side and/or position them sideways, making lateral sleeping difficult and creating discomfort by obstruction of posture and movement.
- Shoulder space is important to allow passengers to take multiple postures in bed. This is often such obstructed in BC seats that passengers actually do not fit into the seat when in bed mode.
- Adjust firmness per area of the mattress for the translation from seat to bed, based on seat inclination and pressure distribution (e.g. activity, posture and antropometrics).
- Choose seat materials (upholstery, padding) allowing breathability. The padding (mattress) should allow movement during sleep, have good isolation and ventilation properties and should be unattractive to dust mites.
- Aircraft movement should be minimised in order to facilitate sleep. When aircraft movement occurs (e.g. turbulence), the sleep opportunity should be lengthened to allow for adequate sleep (e.g. extended period of dimmed cabin light, postpone cabin services).
- Have in BC the headrest sink into the seat surface, forming a part of the mattress, and offer a separate pillow. This mimics better the conditions passengers are used to at home (e.g. freedom of movement). In addition, it is recommended to offer passengers the choice between a European soft ‘flat’, a firm memory foam ‘curved’ and an Asian small rectangular firm cushion, to meet individual preferences. To minimise cabin load, calculations based on nationality and preference data is recommended for an ideal distribution of types of cushions.
- Offer a separate pillow, as passengers are used to at home. A headrest functioning as a pillow will obstruct freedom in movement and posture.



Chapter 6 **Page**

6 IFE comfort in transit

As watching in flight entertainment (IFE) is – like sleeping – one of the major activities during long haul flights, this chapter explores IFE and the context factors influencing watching IFE. The head angle (Delleman, Haslegrave, & Chaffin, 2004), trunk angle (Vink, 2014b), eye angle and the position (screen height and distance) and orientation (angle) of the IFE screen are strongly related to each other (see Figure 6.1). This chapter discusses these factors and the influence on each other, to come with appropriate recommendations on the IFE screen position and head support, so that a neutral an preferred posture is facilitated. Such a neutral position might improve the comfort of watching IFE in the premium cabin.

Note: Major parts of this chapter are included in the ICC2017 conference paper 'Neck posture and muscle activity with and without head support in a reclined sitting posture when watching IFE', as can be found in Appendix B, and in the Applied Ergonomics paper 'Neck posture and muscle activity in a reclined business class aircraft seat watching IFE with and without head support', as can be found in Appendix C.

← **Figure 6.1 | Factors influencing IFE posture**

6.1 A note on the knowledge gab

Most studies concerning neutral viewing angles of the head, neck and eyes focus on visual display units (VDU) with a keyboard and mouse interface at a desk. There is a limited amount of studies on watching TV and IFE screens. It is questionable if VDU study findings are appropriate for watching IFE in the aircraft, as the use of input devices is limited and of the context (e.g. seating inclination) is different. Care is taken to select literature most appropriate to the context for watching IFE within the aircraft, to come with scientific funded insights on improving the comfort of watching IFE in premium aircraft seats.

6.2 Neutral head angle

In designing a headrest for an aircraft seat it is important to define the ideal head position. For the position in the car e.g. Kilincsoy, Wagner, Bengler, Bubb, and Vink (2014) presented comfortable angles, S. A. van Veen, Hiemstra-van Mastrigt, Kamp, and Vink (2014) even in the context of tablet use in a reclined car seat. However, for watching *in flight entertainment* (IFE) in a business class aircraft seat with a reclined trunk, literature is limited. There is however literature on the ideal or neutral head position for sitting with an upright or slightly reclined trunk and standing (see Table 6.1). Recommendations on head angles when using VDU's are described in Delleman et al. (2004) and Psihogios, Sommerich, Mirka, and Moon (2001).

As humans tend to look for equilibrium in their musculoskeletal system for a static posture, the posture of the study of Smulders et al. (in press) without head support can be taken as a neutral head position in the specific IFE context (see Table 14.5). A headrest however should not position the head in this neutral posture, as it is optimised to carry the load through the spine instead of the headrest taking over some of the load. Further research is thus needed on the ideal (neutral) head position for watching IFE/TV in a slouched posture with headrest support. For now, head support close to the 'neutral' head position is recommended.

Table 6.1 | The comfortable (neutral) head position (based on Vink (2016)). See Figure 6.2 for a visual explanation of the given angles.

Reference	Sample size (n)	Condition	Craniocervical angle (NA-v)	Eye-Ear Angle (EEA-h)
Braun and Amundson (1989)	20	Upright sitting, looking straight ahead	38.0°	n.a.
Raine and Twomey (1997)	160	Upright standing, looking straight ahead	41.1°	7.9°
G. M. Johnson (1998)	34	Upright standing, looking straight ahead	40.4°	n.a.
Mon-Williams, Burgess-Limerick, Plooy, and Wann (1999)	12	Upright sitting, listening to music	40.8° ± 6.9	16.2° ± 6.5
		Upright sitting, typing	41.6° ± 8.4	12.4° ± 8.9
Ankrum and Nemeth (2000)	24	Upright sitting, eyes closed	43.7° ± 6.9	7.7° ± 8.1
S. A. van Veen et al. (2014)	10	Reclined sitting (backrest 30°), using a tablet device with arm support	41.2°	n.a.
Smulders et al. (submitted)	21	Slouched sitting (backrest 40°) watching IFE at eye height [1]	29.0° ± 3.6	13.8° ± 5.3

[1] Without head support, screen centre at eye height

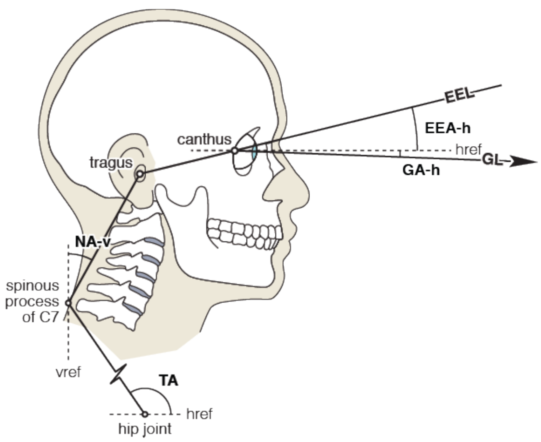


Figure 6.2 | The craniocervical angle/neck angle (NA-v) is defined by a line through the tragus and vertebra prominens (spinous process of C7), and the vertical line. The eye-ear angle (EEA-h) is defined by a line through the tragus and canthus, and the vertical line. Angle representation based on Psihogios et al. (2001). Anatomical representation indicative only.

6.3 Preference for a slouched posture when watching IFE/TV

It is important to determine the preferred postures for an activity in a seat, as the taken posture influences comfort (Naddeo, Cappetti, & D'Oria, 2015; S. A. van Veen et al., 2014) and facilitating a good posture may – on the long run – prevent musculoskeletal injuries (Delleman et al., 2004). When watching *television* (TV) at home and *in flight entertainment* (IFE) during flight, most people prefer to sit in a reclined posture with feet off the ground (see Table 6.2). 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 Table 6.3 and Figure 6.3 for a comparison. Although inclinations are close to each other, a wider range of available backrest inclination is recommended as it could better facilitate individual preferences in seat adjustability for the task performed (Groenesteijn et al., 2009; Smulders et al., 2016).

A possible explanation for the preference for a reclined/slouched posture may be the lower back muscle activity, as shown in the study by Goossens et al. (2003). A study based on an experiment with one subject of Wilke et al. (1999) and a study based on five subjects of Rohlmann, Zander, Graichen, Dreischarf, and Bergmann (2011) may give an indication that a slouched posture also lowers pressure on the intervertebral disks. Although a multitude of in vivo spinal load studies have been conducted (Dreischarf et al., 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).

Table 6.2 | 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	20	Observation / Interview	A slouched posture was taken by subjects as most comfortable for watching TV.
van Rosmalen et al. (2009); (2010)	Watching TV at home in a lounge seat	13	Observation / Questionnaire / Context mapping	Subjects 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.
Filho, Coutinho, and e Silva (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 subjects 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 subjects as most comfortable for watching IFE. Half the subjects rested the head against the backrest and conducted deorsumversion of the eyes (looking 'downward'), where the other half flexed the head forward to watch the IFE screen.

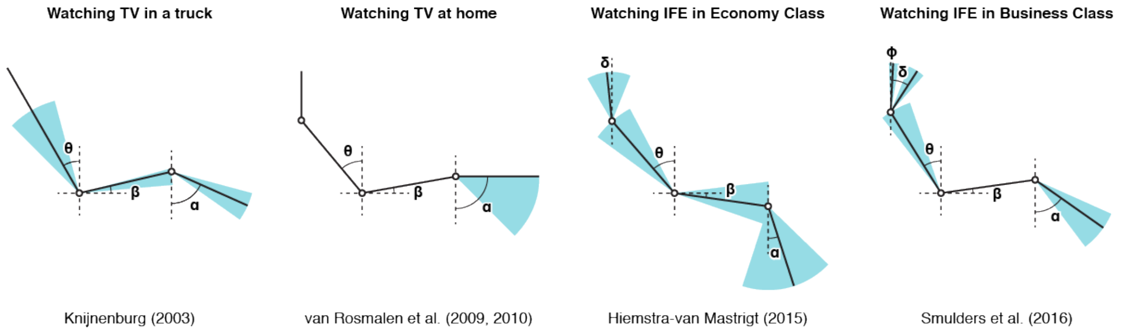


Figure 6.3 | 2D visual representation of seat angles as given in Table 6.3. Black lines represent mean values, where the blue areas represent the observed range (minimal and maximal angles, without outliers) (figure representation based on Hiemstra-van Mastrigt (2015)).

Table 6.3 | Seat/body angle comparison. See Figure 6.3 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]	Not investigated, but was set parallel to backrest
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°) [2]	-8° (SD=6.6°) [2]	41° (SD=6.1°) [2]	-6° (SD=13°) [2]
Smulders et al. (2016)	Watching IFE in a business class seat	10	55° (SD=11.6°)	Not investigated, but was set at 5°	32° (SD=5.6°)	38° (SD=9°) /12° (SD=7°) [3]

[1] Data were acquired by secondary analysis of the study data of Knijnenburg (2005)
[2] Data were acquired by secondary analysis of the study data of Hiemstra-van Mastrigt (2015)
[3] Data were acquired by secondary analysis of the study data of Smulders et al. (2016)

6.4 Neutral eye angle and screen positioning

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. As passengers will watch IFE for a prolonged amount of time (e.g. watching a 1,5-2h movie), the IFE screen should be positioned as such that minimal eyestrain and fatigue would occur, which could cause discomfort.

6.4.1 Preference for downward gaze angle for nearby screens

The preferred gaze angle becomes lower as the viewing distance decreases, as shown in Table 6.3. Also, when an object comes closer than 6m the eyes converge to maintain single vision (Pheasant & Haslegrave, 2005), by contracting the medial recti muscles (Von Noorden & Campos, 2002). A possible explanation for the preference for deorsumversion (looking downward) for nearby objects could be that more activity in the oblique muscles is required for elevation-adduction than for depression-adduction (Remington, 2012), as shown in Figure 6.4. Burgess-Limerick, Plooy, and Mon-Williams (1998) suggest the contraction of the medial recti to compensate incycloduction (creating a divergent force) by the superior oblique when looking upward, could explain the preference. When looking downward the inferior oblique muscles cause depression and excycloduction (creating a vergent force), thus requiring less activity of the medial recti. As prolonged contraction of the medial recti may result in discomfort (Burgess-Limerick et al., 1998), deorsumversion may thus be preferred for looking at a nearby IFE screen. However, proof for this theory could not be found in other literature.

Table 6.4 | Preferred gaze angle (eye-horizon angle) per distance

Reference	Sample size (n)	Seat angles	Arc[1] radius (cm)	Eye-horizon angle
Kroemer and Hill (1986)	n=32	Upright Seat pan: 4.5° Backrest: 90°	Overall	-28.59° ± 11.62
			50	-32.78° ± 11.33
			100	-24.39° ± 10.36
		Reclined Seat pan: 4.5° Backrest: 105°	Overall	-19.58° ± 11.65
			50	-23.14° ± 12.48
			100	-16.02° ± 9.57
Quaranta Leoni, Molle, Scavino, and Dickmann (1994)	n=12	VDU work in upright sitting posture	50	-35° [2]
Burgess-Limerick et al. (1998)	n=12	Self selected by subject	65	≤ -15°
Mon-Williams et al. (1999)	n=6	Upright position, maintaining a constant head position with a horizontal ear-eye line (EEL)	33	-34.33° ± 1.01
			50	-33.00° ± 3.07
			100	-27.42° ± 2.10

[1] Distance of centre of the eye to the screen
[2] -35° was preferred over 0° and +35°.

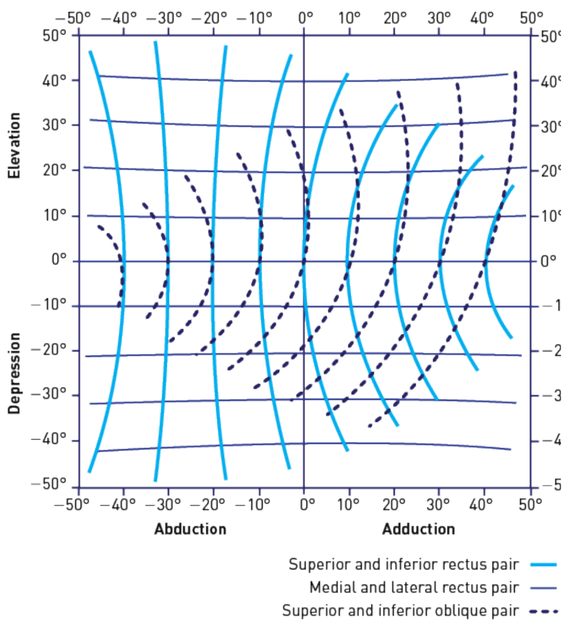


Figure 6.4 | Traces of line of fixation with activity of each of three muscle pairs in various positions of gaze (adaption from Remington (2012), based on theory of Boeder (1961)). For the anatomy of the eye muscles, see Figure 6.5. When adducting the eye for a close object, less activity of the oblique muscles is required for depression then for elevation.

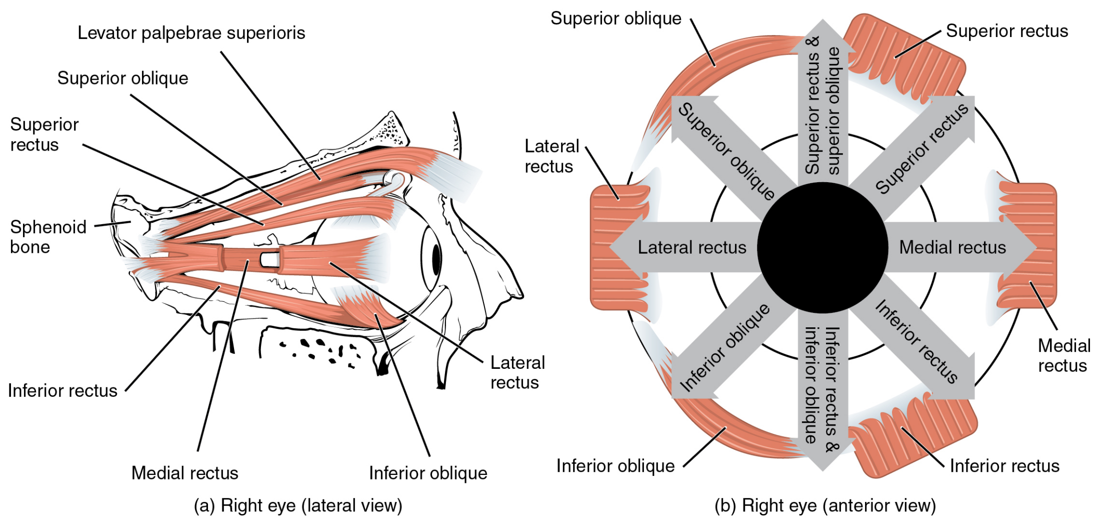


Figure 6.5 | Ocular muscles (based on Ansari and Nadeem (2016) and Remington (2012))

6.4.2 Screen orientation and viewing angle for watching IFE/TV

Psihogios 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 results in other preferred posture, head, neck and eye angles.

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 premium cabins with their bigger screens, more generous space (bigger eye-screen distance, D) and generous backrest recline (θ) (see Figure 6.6). Also Kroemer and Hill (1986) and Mon-Williams et al. (1999) show a more horizontal view is preferred when reclining the backrest and increasing the eye-screen distance. Bauer and Wittig (1998) state it is preferable to have the vision axis horizontal or slightly downward (-17,5˚). A possible explanation for a more horizontal view could be the increased backrest recline, as is preferred when watching IFE/TV (see §0).

Thus, to minimise strain on the eye muscles, limited eye deorsumduction through a horizontal view (or slightly below) on the centre of the IFE screen is recommended.

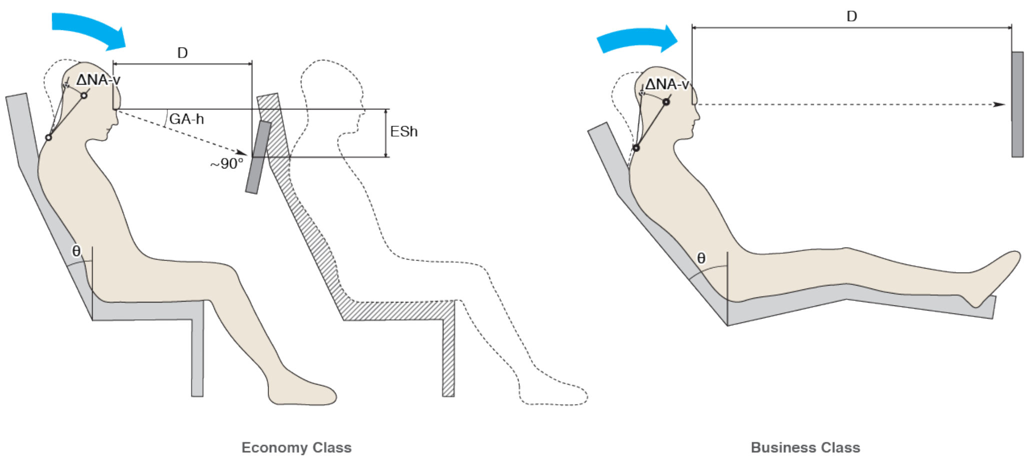


Figure 6.6 | Economy class and business class screen orientation (anatomical representation indicative only).

6.4.3 Viewing distance: a relation between screen size and distance

The shorter the viewing distance, the greater the muscular effort in the eye is needed for accommodation and convergence, which will increase the risk for eye discomfort (Jaschinski-Kruza, 1988; Pheasant & Haslegrave, 2005). However, the further away the screen, the harder it is to see small details. Thus screen size and distance are strongly related. Table 6.5 shows an overview of recommendations on this relation. A viewing distance of 3-4 times the screen width is commonly accepted as preferred.

6.5 Head flexion and the strain on the muscles

When reclining the backrest (30-41˚) in a premium aircraft seat while watching IFE, people tend to or 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 6.7 and Figure 6.8), which was observed in the study by Smulders et al. (2016) (see Appendix A).

When reanalysing the raw data (see Appendix D) from this study, two clear clusters in head position were observed for watching IFE in a BC seat (see also Table 6.3). One cluster is where subjects flexed their head forward with a neck angle (NA-v) of 38˚ on average, by drawing a line through the C7 and tragus vs. vertical (see Figure 6.2 for a visual representation), making no use of the headrest (which was parallel angled with the backrest, which was reclined 32˚ on average). Others extended their head to an NA-v of 12˚ on average, resting it against the headrest and realign their view towards the IFE screen by deorsumversion of the eye (looking downward).

Hiemstra-van Mastrigt (2015) measured a mean head inclination of -6˚ by drawing a line between the *acromion* and the *"tempor"* (probably the *temporalis*). This inclination makes the head extend backwards, probably resting against the backrest. Although the temporalis is – seen from the sagittal plane – relatively close to the tragus at the human skull, the acromion is too distal from the C7 to make a comparison possible. Also the seat pitch – which will have influence on the viewing angle and eye-screen distance – is different (30 inch in the study by Hiemstra-van Mastrigt (2015) and 60 inch in the study by Smulders et al. (2016)), making a comparison difficult.

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 30˚, which according to Delleman et al. (2004) 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; J. Travell, 1967; J. G. Travell & Simons, 1992). A reclined posture increase muscular activity in the neck, which increases the loading on the cervical discs (as cited in Lueder (2004) and Corlett (1999)). Also a static neck posture other than the neutral position might increase the risk of developing pain symptoms in the upper body (Szeto, Straker, & Raine, 2002).

Table 6.5 | TV viewing distance from the eye till the screen (cm), where W is screen width (cm), H is screen height (cm) and S is screen diagonal (inch).

Source	Sample size (n)	Viewing distance					
		Standard Definition (SD)			High Definition (HD)		
		Minimal	Preferred	Maximal	Minimal	Preferred	Maximal
Enoch (1959)	n=12		6,25W				
Gausewitz (1964)	n.a.	5W		14W			
McVey (1970)	n.a.	4W		8W	2W		8W
Ardito, Gunetti, and Visca (1996)	n=15-20		3W/5,2H				
Narita, Kanazawa, and Okano (2001)	n=15				2H/3H		
Sakamoto, Aoyama, Asahara, Yamashita, and Okada (2008)	n=10		3-4H				
Lee (2012)	n=90					3-4W/ 5.3-7.1H	
Yeh and Lee (2012)	n=30					4.3W/7.6H	
Yoichi et al. (2012)	n=27				1.81S+50	3.41S+93	

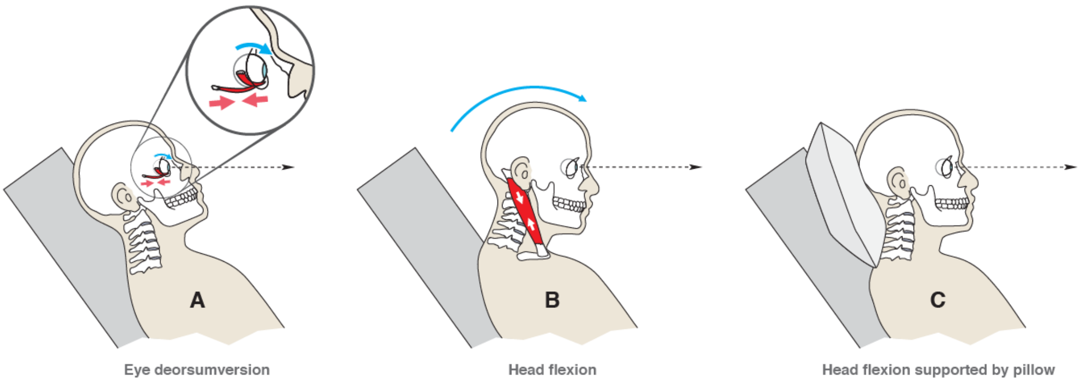


Figure 6.7 | Subject watching IFE in slouched posture while A) deorsumducting the eyes by contracting a.o. the m. inferior rectus and m. inferior oblique B) flexing the head forward with respect to the trunk by contracting a.o. the m. sternocleidomastoid and C) flexing the head forward while gaining support of a pillow (anatomical representations indicative only).

Figure 6.8 | Subject watching IFE in slouched posture while A) deorsumducting the eyes by contracting a.o. the m. inferior rectus and m. inferior oblique B) flexing the head forward with respect to the trunk by contracting a.o. the m. sternocleidomastoid (from Smulders et al. (2016))

6.5.1 Need for head support

It can be presumed that passengers look for support when flexing the head forward by using a pillow (see C in Figure 6.7), which is commonly supplied to passengers on long haul flights. Such behaviour has been observed in the study of Vink et al. (2017) among frequent BCP. Also, in the studies of van Rosmalen et al. (2009) and Smulders et al. (2016) it was observed that subjects lacked neck/head support when watching TV/IFE in the slouched posture at home and in BC. In the study performed by Hiemstra-van Mastrigt (2015) subjects reported discomfort in the neck when watching IFE in an economy aircraft seat. Bauer and Wittig (1998) found that head extension for upward looking at a screen is perceived as uncomfortable in a backward (20˚ recline) sitting posture, possibly due to the lack of head support. In a context mapping study by van Rosmalen et al. (2010) for a TV lounge seat, subjects requested a headrest for head support. Tilley (1993) recommends the use of a headrest and leg support when reclining 30˚ or more. In the study of Smulders et al. (submitted) (see Appendix C), subjects expected to experience more comfort when having head support by a headrest for watching IFE in a slouched posture for a prolonged amount of time.

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 (static) position. In a study by Y. 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 could increase the activity of the flexion muscles to maintain (static) position. Bauer and Wittig (1998) states that the greater the inclination of the axis of vision, the greater the muscle activity in neck. However, Straker, Pollock, Burgess-Limerick, Skoss, and Coleman (2008) state that higher screen orientation (thus extension of the neck) has no significant effect on the upper musculus trapezius and the cervical erector spinae compared to a low screen orientation (flexion of the neck). The question is whether this is the case in the context of watching IFE in a slouched posture. This could be answered by using a biomechanical model and *electromyography* (EMG); see §6.5.3.

6.5.2 Need for arm support

van Rosmalen et al. (2010) also observed a frequent use of the armrest when watching TV. It is used for balance when reaching for something close to the seat, to lean on it and to come out of the seat. The arms also have influence on the experienced comfort in the shoulders and neck. The arms weight together 10% of the human body (De Leva, 1996; Snijders et al., 1995), putting quite some strain on the shoulders and spine (Snijders et al., 1995). When the arms are not well supported in the seat, the load is fully carried by the shoulders, demanding muscle tension in the shoulders and neck which is uncomfortable over a longer period of time (Snijders et al., 1995). A correct armrest height is therefore of importance to the experienced comfort in the shoulders and neck. To make sure most percentiles will have support, it is preferred to have a too high armrest than a too low one (Snider, 2016).

It is thus important to consider arm support for the watching IFE posture. As this project focuses on the headrest, arm support is considered out of scope. For further reading on improving armrest support for IFE, the graduation thesis of Vledder (2017) *Redesign of a business class armrest: Improvement of arm comfort for watching in flight entertainment and reading* is recommended.

6.5.3 Neck muscle activity study

Neck flexion theoretically stretches the muscles posterior to the movement axis and contracts the neck muscles anterior to the movement axis. In cooperation with prof.dr. A. Naddeo and prof. N. Capetti of the University of Salerno, a simulation with the musculoskeletal AnyBody™ model (see Figure 6.9) was conducted. The simulation showed that neck muscle activity decreases (see Figure 6.10) when the head flexes to gain a horizontal view, while the backrest was reclined at 40˚ and the back, buttocks, upper legs and lower arms were supported. In another 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 Figure 6.10). 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 clavicular (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 lateral rotation axis in the neck.▸

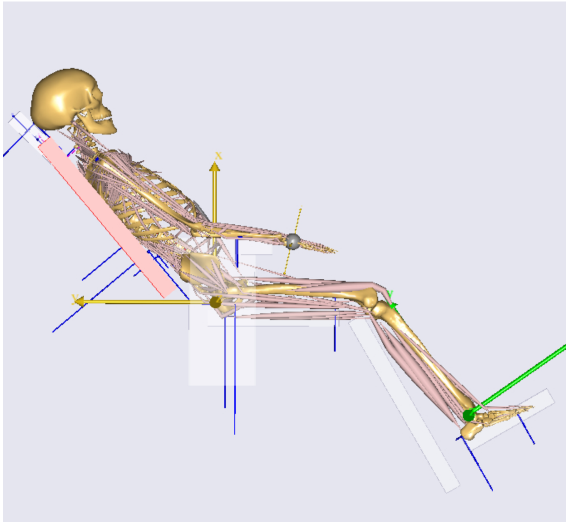


Figure 6.9 | Musculoskeletal model with supported back, buttocks, upper legs and lower arms (AnyBody Technology A/S, Aalborg, Denmark).

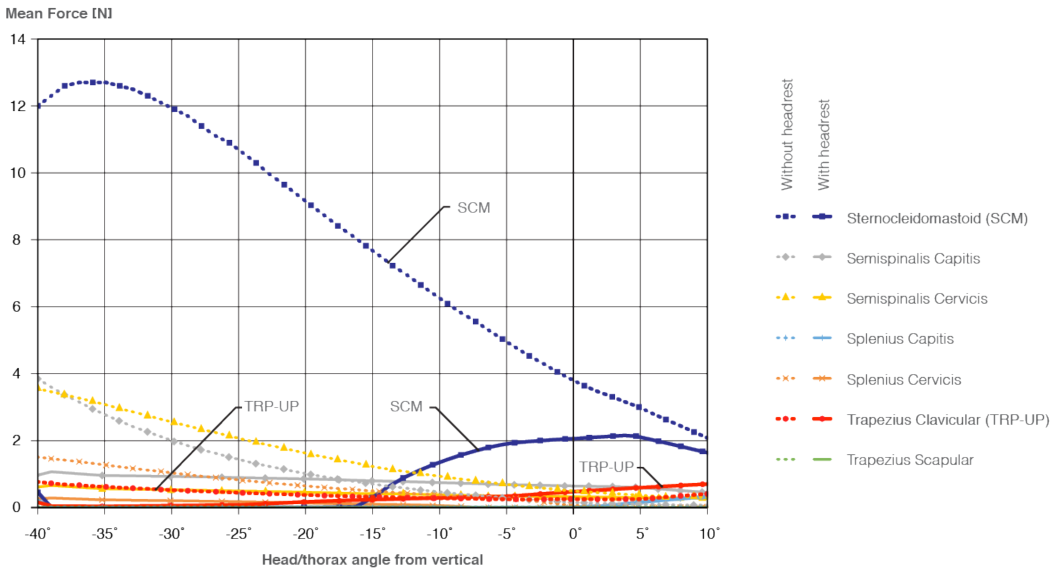


Figure 6.10 | AnyBody™ simulation of mean muscle forces [N] when head flexes from parallel to backrest (set at -40°) to upright (0˚) and beyond (till 10˚).

- To study 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, an EMG and comfort study on 21 subjects was conducted (see Appendix C). Despite the expected differences in muscle activity based on the AnyBody™ simulation, no significant differences was found in the musculus sternocleidomastoid and musculus trapezius pars descendant between the conditions with headrest and without headrest (see Figure 6.11).

However, a significant difference in *expected comfort rating* was found. Subjects indicated they expect to experience more comfort with a headrest when watching IFE for duration of two movies during a long haul flight (see Figure 6.12). This study also found a significant difference in posture (see Table 6.6 and Figure 6.13). 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 necessary 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.

For a full overview of the findings, please see Smulders et al. (submitted) *Neck posture and muscle activity in a reclined business class aircraft seat watching IFE with and without head support* in Appendix C.

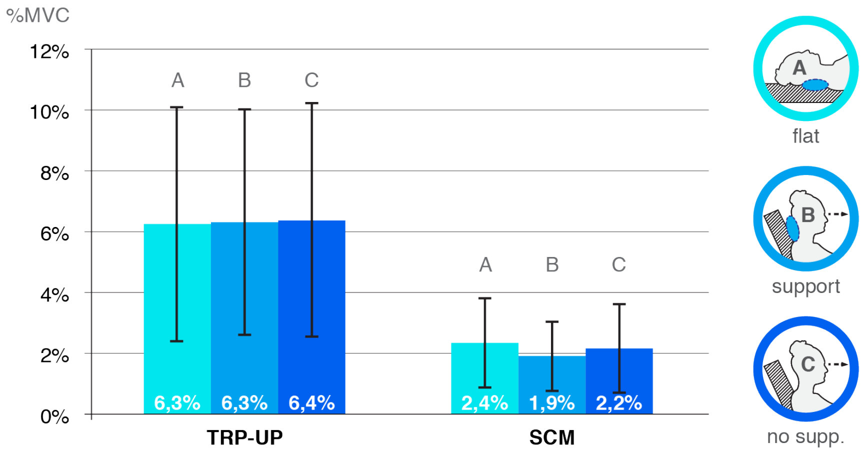


Figure 6.11 | Mean muscle activity as a percentage of MVC (n=19)

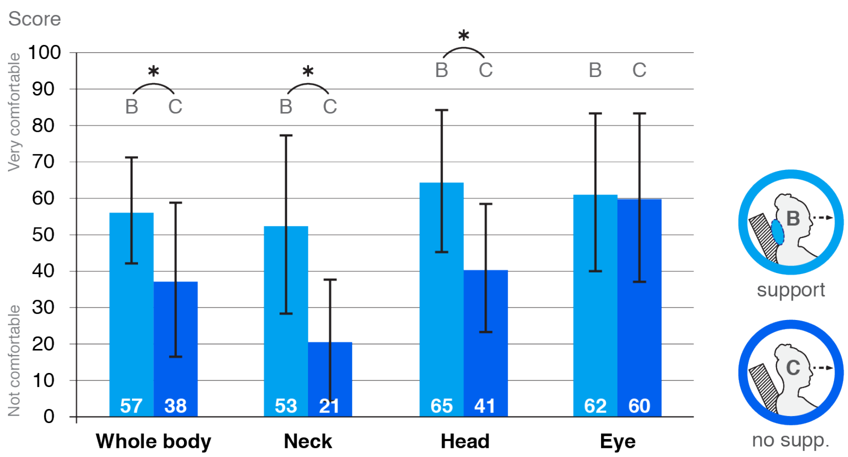


Figure 6.12 | Mean comfort scores with SD (n=20)

Table 6.7 | 2D posture inclinations.
See Figure 6.13 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	0.00018 *		0.00014 *		0.00012 *		0.00578 *	

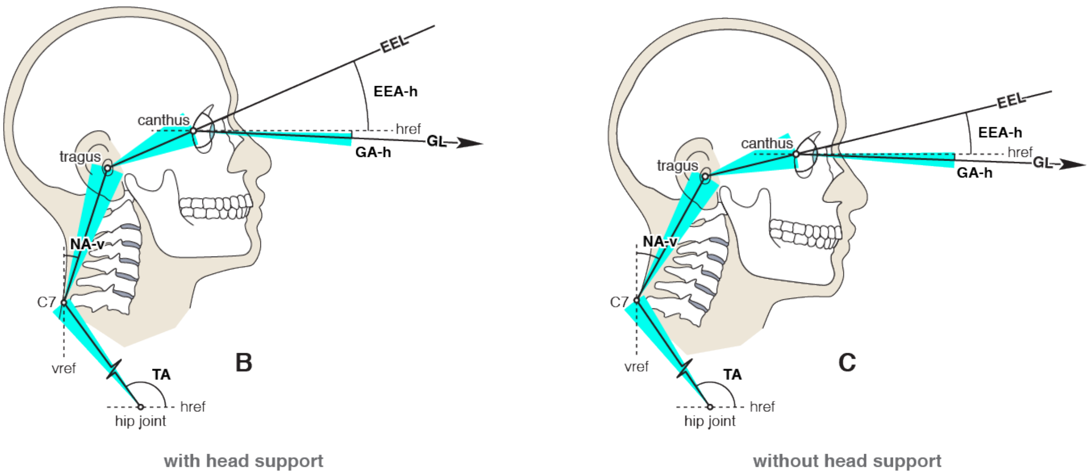


Figure 6.13 | 2D posture angles (anatomical representation indicative only).
Left: condition B, with head support. Right: condition C, without head support. Black lines represent mean values, where the blue areas represent the observed range (minimal and maximal angles). The given angles: TA: Trunk Angle (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).

6.6 IFE challenges in the premium cabin

6.6.1 Screen misalignment issues in BC

In the study of the Vink et al. (2017) frequent BC flyers stated that some IFE screens were too close or too big, and that they would like to have the possibility to set the screen at an upward (for tall people or to prevent glare) or downward angle (for small people or for when lying in full flat mode just before sleep). As stated before, a horizontal viewing angle is most preferred, preventing prolonged flexion or extension of the neck and eye sursumversion (looking up) and deorsumversion (looking down). In that study Vink et al. (2017) it was also observed that screens of some investigated BC seats were off-centre and were not at the adequate eye height, potentially causing misbalanced postures (e.g. torso rotation, head inclination and eye deorsumversion) and thereby could cause discomfort. Thus screen orientation and height adjustability and an appropriate screen size (see §6.4.3) are important for a comfortable IFE experience in BC.

6.6.2 Screen misalignment issues in PEC

Where in BC IFE screens are mounted on the seat shell (and thus stay in the same position), in PEC the IFE screen is commonly mounted on the backrest of the seat in front. This poses a multitude of issues, as it is often mounted relative low and adjustment is limited.

As stated by Yoichi et al. (2012), the ideal viewing angle should be 90˚. As can be seen in Figure 6.14, eye height greatly differs between an international P95 male and a P5 woman (J. F. M. Molenbroek, 2004), resulting in that the majority of the population has to look down. This requires and/or neck flexion and eye deorsumversion, wich as discussed earlyer, may cause discomfort and pain in the neck and shoulder.

When the seat in front reclines, the orientation and height of the IFE screen will change (see Figure 6.15). First of all passengers already do not like that their personal space gets invaded, nevertheless that they now have a misaligned screen, which they manually have to adjust. But since adjustability of the IFE screen is limited (often hinging slightly forward), most passengers have to adjust their posture as well, limiting them to take their preferred and more comfortable postures. Also due to height difference, passengers have to compensate by bend their head to get a perpendicular view to their IFE screen. When watching IFE for a prolongued amount of time, again, this may cause fatigue and discomfort in the neck and shoulder region. Also when the passenger reclines himself (see Figure 6.16), IFE viewing height, angle and distance changes. This can have a negative impact on viewing comfort, since screen size and distance are related (Yoichi et al., 2012) and viewing angle can negatively the passenger's posture.

As eye height difference is too extensive to come with a compromising height, adjustability of the IFE screen is advised. One way is to have the screen at P95 male eye height in a slouched posture and rotate forward to accommodate shorter people. Another option is vertical translation of the screen up and down, meeting its maximum at slouched P95 male eye height and slouched P5 female height. Forward and backward rotation is less ideal, as this requires flexion of a P95 male and extension of a P5 female, which may result in discomfort.

Thus screen orientation and height adjustability are important for a comfortable IFE experience in PEC.

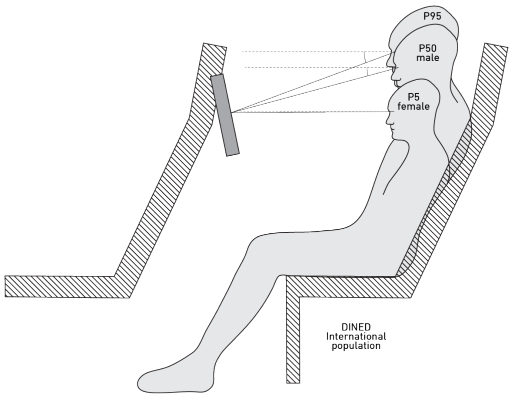


Figure 6.14 | The limited adaptability of the IFE screen requires adjustment of the passenger for multiple international population percentiles, instead of adjusting the IFE screen angle and height.

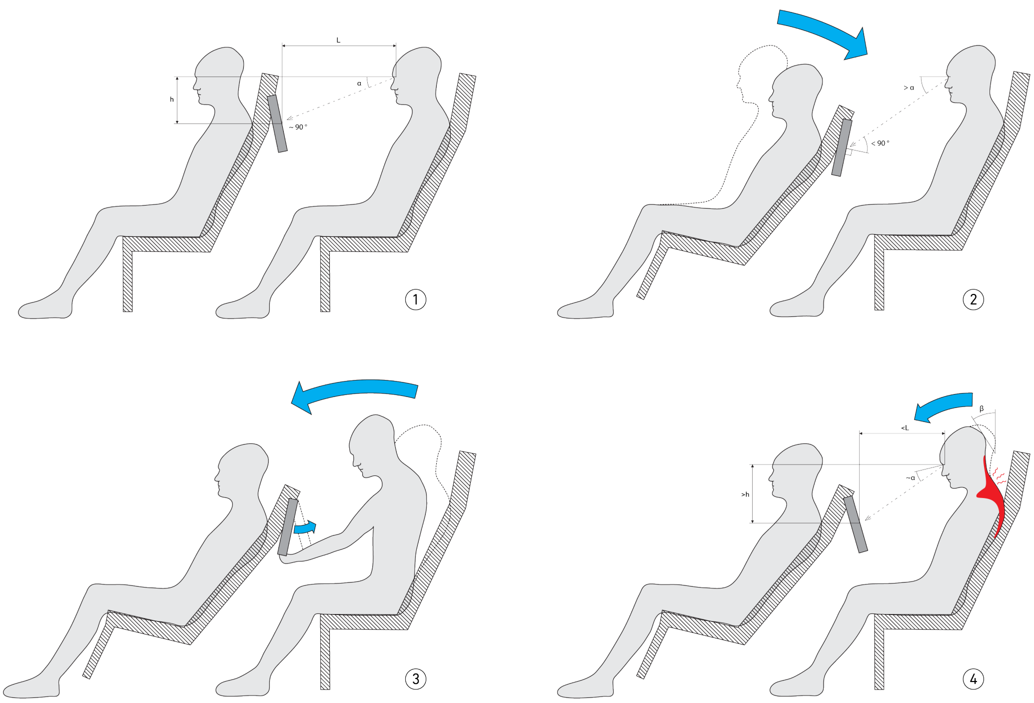


Figure 6.15 | When the seat in front reclines, the passenger behind has to adjust the IFE screen angle (which is limited) and adjust posture to cope with the decrease in height, angle and distance. This forced adaption of a more strenuous posture may cause discomfort.

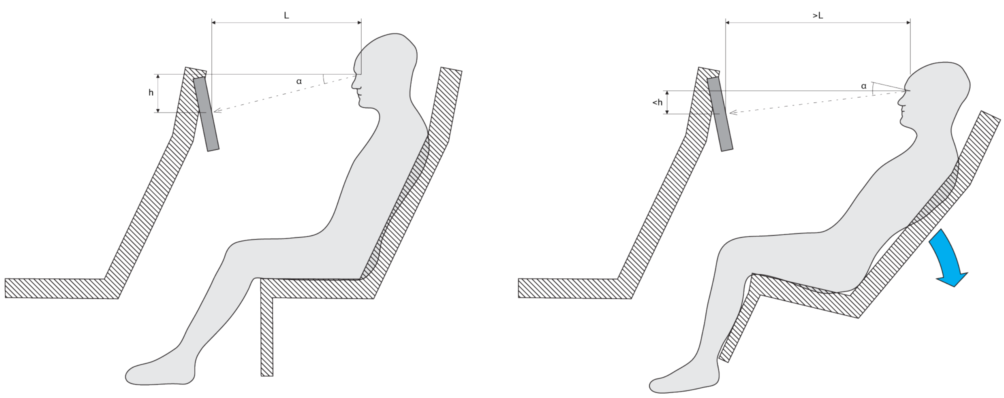


Figure 6.16 | IFE viewing height, angle and distance difference when reclining. This may require the passenger to conduct eye deorsumversion or flex the head forward.

6.7 Conclusion

For watching IFE in premium cabins, a balance needs to be found between posture and screen orientation, finding minimal strain on the musculoskeletal system. As stated in §4.6, facilitating postures in seating is important to comfort. Since the slouched post is most preferred for watching IFE, this should be the starting point, as it will dictate the screen orientation. That said, literature suggests that the further away the IFE screens, the more horizontal (or slightly below) the view on the centre of the IFE screen should be, to minimise strain on the eye muscles. This is the case in premium cabins, where, especially in BC, eye screen distance is significant bigger than in economy. The IFE screen centre should thus be placed at eye height, perpendicular to the line of sight, where the screen size should be dependent on the eye-screen distance (see §6.3.3). A viewing distance of 3-4 times the screen width is commonly accepted as preferred.

In this position a more upright head is neutral, but lacks support, as the passenger has to sustain static position. Head support is advised for watching IFE in a slouched posture, as it will improve the expected comfort of passengers. It may also lower muscle tension/fatigue, but further long-term research is needed. Head support should be angled slightly backwards to that the head will take not the neutral head position, but is supported as such that the headrest will carry load of the head. Otherwise the headrest would be counter effective, pushing the head forward and requiring counteraction of extension muscles to sustain static position. It is also important that this head support should be optional and adjustable, so passengers are in control and can adopt multiple postures. Clear usecues are thus important here in the headrest design.

Note on placing IFE screen above the passenger
No flexion of the head is also an option, as the head will rest on the backrest of the seat. This requires the IFE screen to be placed above the seat for a perpendicular view to prevent deorsumversion of the eyes. This however is not an option, as regulations require that cabin crew have an overview of the cabin at all times. Placement of IFE screens in the overhead luggage bins can be an option, but requires big investments in R&D, certification and manufacturing (e.g. heat regulation of IFE systems, restructure cabling in the fuselage by the aircraft manufacturer, etc.). VR or nearby positioning of the IFE screen such as proposed by Van der Klooster (2015) may be an option, however it is the question if premium class passengers accept this. Therefore this project searches to improve the comfort in a more conventional matter.

6.7.1 IFE design challenge business class

- Limited height and angle adjustability of IFE screen
- Head/neck support for slouched posture when watching IFE

6.7.2 IFE design challenge premium economy

- Limited height and angle adjustability of IFE screen
- Wrong screen height and orientation when seat in front reclines
- Head/neck support for slouched posture when watching IFE

6.7.3 Recommendation for further research and development

As literature on watching TV and IFE is very limited, there is a knowledge gab, which with the introduction of autonomous driving becomes even more relevant. For further research it is therefore recommended, e.g. by making an overview of existing IFE/VDU related literature, followed by a study specifically on the context of IFE (e.g. in aviation and autonomous driving) to give more suitable recommendations for the industry.

Further research is also advised on the ideal angle of support by and the long-term effects of the use of a headrest when watching IFE in a slouched posture on comfort, discomfort and fatigue, as in real life passengers will watch IFE for a prolonged amount of time during long-haul flights (e.g. watching multiple movies). Pleas see Appendix C for a full recommendation.

6.8 Further reading

For further reading Yoichi et al. (2012) *Ergonomic Design Guidelines for Flat Panel Display Televisions* is recommended, as it is the only and most comprehensive document on TV ergonomics. For more information on vision and the eyes, Delleman et al. (2004) *Working Postures and Movements* is recommended. For further reading on watching IFE in premium cabins, Smulders et al. (submitted) *Neck posture and muscle activity in a reclined business class aircraft seat watching IFE with and without head support* is recommended, and can be found in Appendix C. For further reading on improving armrest support, the graduation thesis of Vledder (2017) *Redesign of a business class armrest: Improvement of arm comfort for watching in flight entertainment and reading* is recommended. For further reading on aircraft seating anthropometrics, Molenbroek et al. (2017) *Anthropometric study to update minimum aircraft seating standards* and Quigley et al. (2001) *Anthropometric study to update minimum aircraft seating standards* is recommended.

6.9 Recommendations for seat manufacturers and airlines

The consideration, exploration and/or implementation of the following recommendations – based on previously discussed literature research, experiments and insights of the author – are advised:

Posture support

- Facilitate a slouched posture (backrest recline of 40˚ and leg support) for watching IFE.
- Allow posture differences (e.g. upright and different recline angles).
- Facilitate close to neutral head support, where load is distributed partly onto the headrest.
- Provide adjustable arm support, to minimise strain on neck and shoulder muscles. If adjustment in not possible, a high armrest is preferred to serve a larger population.

IFE screen position

- Position the centre of the screen at eye height or just below (above is less comfortable).
- The IFE screen should be perpendicular to glare line.
- The centre of the IFE screen should be aligned with the centre of the seat.
- Choose screen size based on eye-screen distance (see §6.3.3).
- A minimal comfortable viewing distance is considered 500 mm, where 750 mm is more preferable.
- Provide angle adjustment of the IFE screen to facilitate multiple postures and larger population.
- IFE screen height (measured from the floor to screen centre) adjustability of 240 mm is recommended, to facilitate from an Asian P5 female up to a Dutch P95 male. [§4.4.3.2]

7 Design vision, challenges and requirements

This chapter first discusses – based on the context, sleeping and watching IFE in transit analysis – the design vision, challenges and requirements. These directed the ideation phase, where solutions to problems in the premium cabins were generated and combined.

7.1 Design vision

Passengers are limited in their physical and psychological freedom in an aircraft, opposed to what they are used to on the ground at home, in the office, in the car, etc. In the air passengers are mainly fixed to their seat and are subjected to the pre-defined service routine of the cabin staff. The hypothesis is that to be able to perform the activities and corresponding postures the passenger is used to at home, and giving them more control of their condition, will improve the comfort experience by feeling less trapped and limited, and may benefit the passenger physical well being, by improve the quality of sleep and watching *in flight entertainment* (IFE). As sleeping in the aircraft is difficult (strange environment, noise, etc), making the bed (seat) feel like at home as much as possible will help passengers to fall asleep, keep asleep and reach easier deep sleep. As people prefer different postures in watching IFE, variation of postures should be possible while watching IFE for a better (comfort) experience. This results in the following design vision:

> *Mimicking the conditions aircraft passengers are used to at home when watching TV (IFE) and sleep as much as possible will make them feel familiar and less restricted, improving their comfort experience.*

7.2 Design challenges

Based on the context, sleeping and watching IFE in transit analysis, and design vision, the following design challenges were formulated:

The main problems in BC concerning sleep are the lack of control and the difference in required pressure distribution between seating and flat sleeping. A new seating concept could offer more control and change the pressure distribution according to posture and anthropometrics.

The main problem in PEC concerning sleep is the limited recline, as gravity will make the head fall sideways, causing the 'falling motion effect' (see §5.7.2). Current side flaps in headrests are not sufficient, as passengers tend to slide out of them. A new headrest design supporting the head could prevent this, improving the quality of sleep.

The main problem in both BC and PEC concerning watching IFE is that IFE screens are often incorrect positioned and current adjustment features are too limited. Passengers are also lacking head support for watching IFE in a slouched posture. Another problem specific to PEC is when the seat in front reclines the IFE screen gets misaligned, making the passenger take bad postures. A new headrest design could support the head, where a new IFE design could improve the adjustability of the screen height and orientation.

7.3 Design requirements

As discussed before, cabin classes have their restricted in possibilities. Where there is more physical room and design freedom in business class (a seat may weigh and cost more), in premium economy space is more restricted, as are costs. To honour the design vision as much as possible, the following main requirements are defined:

A business class aircraft seat should:

- Facilitate a flat sleeping surface
- Allow movement during sleep
- Give control over own conditions
- Supporting different postures when watching IFE
- A straight view on the IFE screen

A premium economy class aircraft seat should:

- Recline as much as possible (the flatter, the better)
- Supporting the head during sleep in limited recline
- Allow movement during sleep
- Supporting different postures when watching IFE
- A straight view on the IFE screen

Additional requirements:

Maintenance and durability

1. Lifespan of at least 15 years without maintenance (maintenance only required when damaged)
2. Component should operate reliably and handle miss-use and molest.
3. The headrest should be removable without tools (or very quickly/easily), as repairing within the cabin is not possible due to quick turnarounds.

Hygiene

4. Headrest should be easily cleanable.
5. Antimacassar should cover contact area.
6. Dress cover should be easy to remove and place, as covers are monthly washed.

Safety

7. Compliant with aviation regulations and standards.
8. No obstruction of cabin view and crew procedures.
9. Headrest should not exceed seat height.
10. Prevent hair and fingers get stuck and/or cut by headrest (prevent access to moving parts).

Headrest shape

11. Freedom of movement and posture.
12. Headrest support for ~P5-P95.
13. Flat profile headrest and free shoulder space.
14. Adjustable neck support (headrest curvature).
15. Soft neck support and firm head support.
16. Soft cheek support and firm head and jaw support.

Sleep

17. Cool and breathable pillow
18. Prevent 'falling motion effect' trough the prevention of sliding and nodding of the head
19. Enable lateral posture/leaning sideways
20. Isolating and breathing mattress
21. Mattress should allow movement during sleep
22. Prevent disturbance by sound
23. Prevent disturbance by light
24. Create private environment for sleep
25. Give passengers more control of their situation and environment
26. In seat climate control (microclimate temperature)

IFE requirements

27. Unobstructed view on the IFE screen.
28. Centre of IFE screen at eye height.
29. Head and neck support in slouched posture when watching IFE.
30. IFE screen should not obstruct cabin overview: The screen cannot translate in height above the seat, due to FAA regulations considering cabin overview; FA's should be able to see all passengers. An elevated IFE will obstruct the view.

Other

31. No limitation in ingress and egress by the passenger.
32. Usable when reclined.
33. Usable by P5-P95 population of passengers.
34. Adjustable in height.
35. Prevent neck strain.
36. Headrest should stay within seat space anvelope.
37. Keep the shoulders free.
38. Weight should be in range of current headrests.

There are also other requirements, in majority safety and strength regulations and certification requirements. These are not explicitly tackled, as the design phase would be too restricted. However, these restrictions are always kept in mind. Further development by engineering (e.g. trough FEM analysis) and crash testing is required for certification.

Safety requirements (Zodiac Aerospace, 2016c):

- FAA Technical Standard Order (TSO) C127 certification
- FAA 16G and Head Impact Criteria (HIC) certification

Structural strength and reliability testing (Zodiac Aerospace, 2016c):

- Cycle testing of all moving parts and attachments
- Abuse testing of arms, backs, tray tables, and video arms
- AS8049 and ARP-5526 standard loading procedures
- Complete flammability as well as heat release, smoke density, and toxicity testing of all non-metallic parts used on our seats

Chapter 8 **Page**

8 Concept design

This chapter discusses a selection of the most promising concepts and ideas, followed by a brief elaboration on some trough paper prototyping and CAD simulation. These concepts may inspire further research and development, as will be discussed in chapter 9. For a full overview of all ideas and sketches made, please see Appendix E.

8.1 Premium cabin concepts for sleep and IFE

Based on the program of requirements and design vision, a multitude of ideas and concepts were generated to tackle the found problems and design challenges. A selection of the most promising ideas and concepts, which are in the opinion of the author worth investigating further, are discussed below. For a full overview of all ideas and sketches made, please see Appendix E.

8.1.1 Auto-adjusting BC bed with personalisation and control features

BCP's complaint about the lack of control within the cabin. There are also issues like getting woken up by flight attendants (FA) for cabin services and checks, decreasing sleep efficiency. Disturbing factors like cabin sounds, high/low temperature, light pollution and lack of privacy pose problems to falling asleep and keeping asleep. Also the change in support requirements for different activities (e.g. sleeping and sitting) pose a challenge. This concept tackles multiple problems and tries to integrate them in one single concept, see Figure 8.1.

#1 Decide

On the IFE screen a timeline is shown to the passenger with an overview of the cabin services during flight. The passenger can select which services he/she wishes to make use of and thus make an entire personal flight schedule. When the passenger want to schedule sleep during flight, wake up times are advised based on sleep cycles.

The made schedule and selected cabin services are communicated to the FA's by a display in the galley or other digital system (e.g. a tablet), showing details of service such as time, what to prepare for what amount of passengers, special requests (e.g. vegetarian, vegan, halal), etc. This allows FA's to get informed about which services passengers would like to join at what times, giving passengers more control (opposed of being forced to follow the cabin regime) and helps FA's to work efficiently.

Note: such an integration of seating, cabin and galley products may be very interesting for Zodiac Aerospace, as it has a broad portfolio of products. By providing airliners with such integrated options, airliners may be persuaded to by complete Zodiac cabins.

#2 Sleep

Passenger can be helped to fall asleep by e.g. speakers in the headrest or a noise cancelling headphone, which can provide music, forest/sea/city sounds, podcasts, etc. Also the head end of the seat is kept cool, to improve sleep latency and deep sleep. A sound damping shell (soft padded lining on the inside) can damp surrounding sounds and provides a sense of privacy. Furthermore, slowly shifting cabin and in seat lighting to red colours can help passengers to prepare for sleep. In addition, heating the seat slightly before sleep may improve sleep on set. To help the passenger to fall and stay asleep, the cabin temperature can be cooled down to 18-22˚C. Active temperature control of the seat with temperature sensors in the mattress can keep the microclimate temperature between 27-29˚C. The passenger can adjust this temperature according to personal preference.

The status monitor on the side of the seat shell helps FA's to see at a glance what the status is of the passenger, who to serve and who not to bother or who to wake up. It also shows at a glance (just like on the screen in the galley) who has their seatbelt on, making a cabin check quicker and saver, with minimal passenger disturbance.

#3 Awakening

With fading in blue light and increasing in seat and cabin temperature, with the addition of sound and vibration, the passenger can be woken up slowly at the appropriate time at the end of REM (or in S1 sleep). By monitoring passenger movement with pressure sensors in the mattress, an estimate of the sleeping stage can be made. This assures that passengers feel more rested and wakes up in time for TTL, joining cabin services (e.g. breakfast) or other personally scheduled activities.

Active seat firmness adjustability

To provide all passengers with optimal support, the firmness per area of the bed adjusts automatically based on the passenger anthropometrics and activity. A microcontroller can determine the weight distribution and taken posture with pressure sensors within the mattress, controlling seat firmness per area. As this was not the main topic of this project, no further exploration on mechanism design was conducted. Inspiration could be derived from Verhaert, Haex, Wilde, et al. (2011) and Park, Kim, Min, Kwon, and Jeong (2000).

To summarise all features:

- Automatic adjusting firmness per area based on anthropometrics and activity
- Self-planning of trip (incl. opting in/out of cabin services)
- Features to fall asleep (light, sound damping)
- Features to keep asleep (sound damping, privacy)
- Features to be pleasurably woken according to personal schedule (based on sleep stage and planning by natural features as sound, temperature and light)
- Communication of wearing belt and preferences to cabin crew to prevent disturbance. Opportunity for Zodiac Aerospace to combine products in the portfolio (seats + galleys).
- Cool pillow to improve sleep latency and deep sleep
- Sleep cycle wake-up system with sound, light and warmth (simulating rising sun)

Note: this design was part of the original assignment of designing a full flat long-haul BC seat (see §1.3), which has been discontinued.

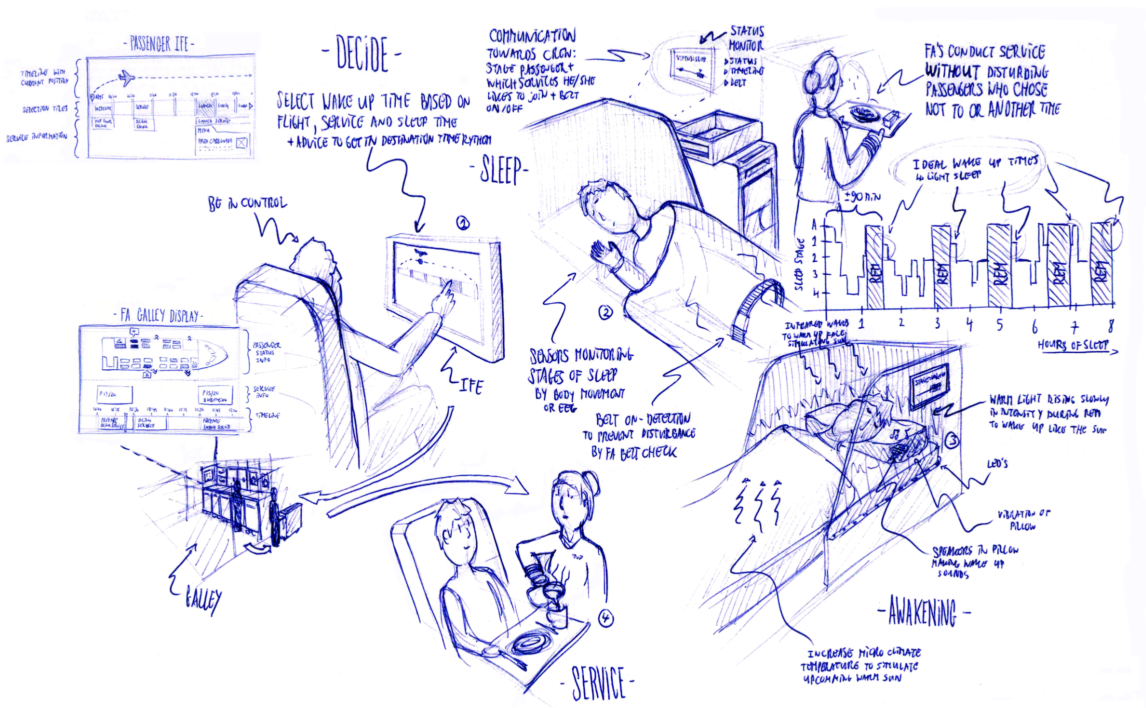


Figure 8.1 | Auto-adjusting BC bed with personalisation and control features. Note:

8.1.2 Headrest for PEC sleeping with limited recline

In sleeping with limited recline in PEC is difficult due to gravity on the head, causing the ‘falling motion effect’ (see §5.7.2). Current side flaps in e.g. economy class seats are not sufficient, as people tend to slide out of them. The following two designs intend to provide support by carrying the head in such a way it does not slide downward, triggering the sleep wake system, while allowing the head to keep moving as posture change in sleep is natural.

8.1.2.1 Folding headrest for PEC sleeping with limited recline

This design contains two options, each with its benefits and downsides. Design B (see B1-4 in Figure 8.2) is a slimmer but wider design, which spans over the entire width of the seat. As traditional headrests, the side flaps can be folded towards the inside. The downside is that all the weight of the head needs to be carried by the friction hinges, which may make the side flaps wiggle. In both design A and B the flaps can be rotated downward (see right bottom in Figure 8.2), creating a bowl shaped support surface. This prevents the head of sliding down, while it provides sufficient room to move from side to side, allowing natural movement.

Design A (see A1-3 and B4 in Figure 8.2) folds from in to out, which makes the headrest thicker as padding both on the in and outside are needed. It also creates a gab, which might be bothersome when not making use of the flaps. This construction is however more rigid, as the hinge stops at ~90°, as it cannot bend further. One of the major downsides of current headrest side flaps is that the head slides off. Chin support carries the load of the head (see top right in Figure 8.2), preventing unpleasant shear forces on the check skin and prevents sliding off of the head. As the headrest folds inwards, the chin support folds underneath the back of the headrest.

Concerning the use of padding in both designs, the upper side of the head and the chin are less sensitive and can carry loads (see §0). The chin support and upper part of the side flaps should thus be padded with firm foam (see A3 in Figure 8.2). As the cheeks are more sensitive, soft padding should be placed here.

This design makes use of simple mechanisms, which are already in use in aviation, meaning they have proven its reliability and has been certified. Although further development is needed, the design may have a relative short time to market.

To summarise all features:

- Prevention of the ‘falling motion effect’ by ‘catching’ the head when sliding sideways
- Chin and jawbone support
- Allows movement (and postural change) as is natural during sleep
- Folding and rotation operation based on reliable and certified (friction hinge) mechanisms

8.1.2.2 Following headrest for PEC sleeping with limited recline

This headrest design is a compact rigid headrest with (V-shape) side flaps and chin support. The headrest can articulate, following the head to allow natural in sleep movement (see left in Figure 8.3). When the head moves sideways (over the Z-axis), the headrest twists (over the Y-axis) ‘catching’ the head (see right Figure 8.3, showing the movement), preventing the head to fall down. A small force – e.g. generated by a torsion spring – counteracts this movement, bringing the headrest always in an (neutral) upright position when carrying no load. Multiple mechanisms were developed to articulate the headrest, of which some can be found in Appendix E. Three designs (an hinge with arm, ball joint connected rods and a slider track) showed promise and were further explored as discussed in §8.2.3.

- To summarise all features:
- Prevention of the ‘falling motion effect’ by ‘catching’ the head when sliding sideways
- Chin and jawbone support
- Allows movement (and postural change) as is natural during sleep
- Moves with user, so headrest can be compact

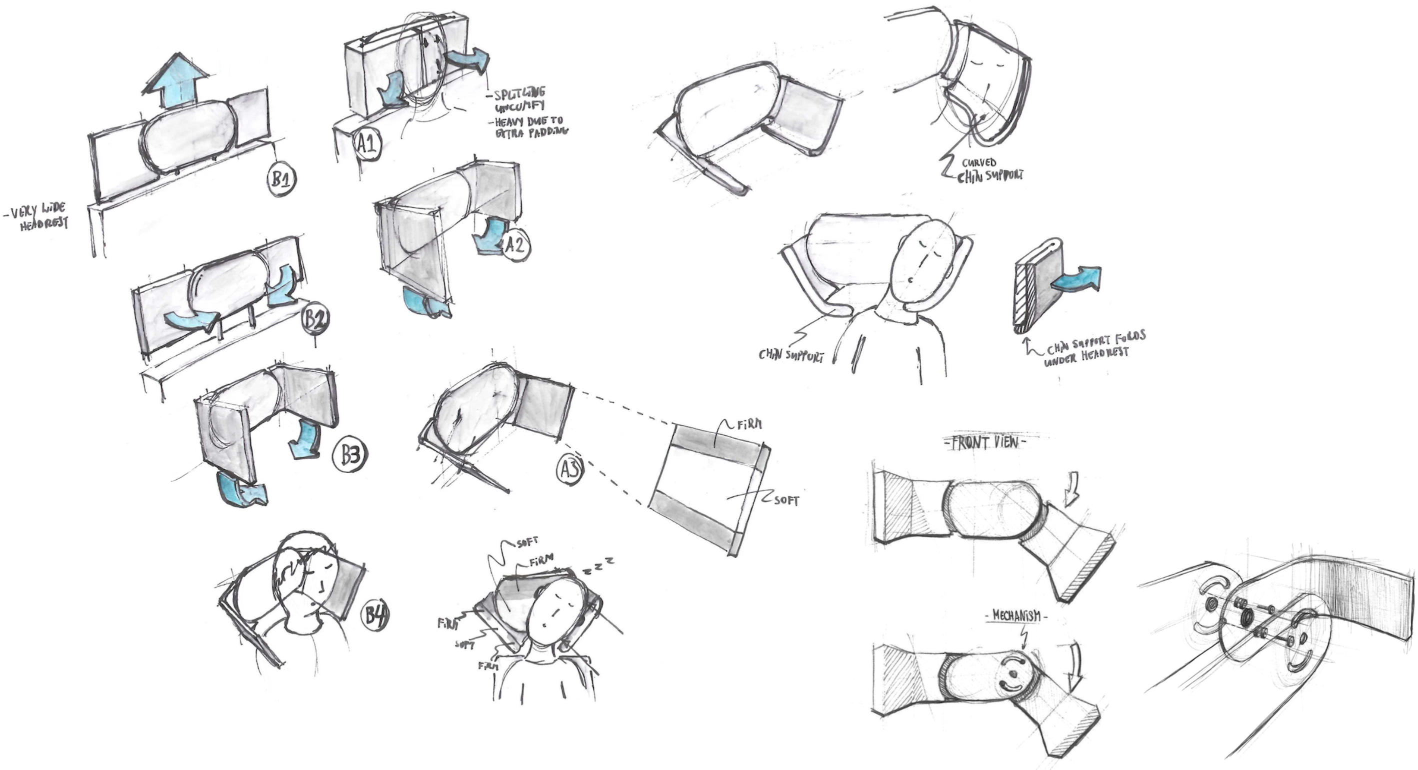


Figure 8.2 | Static headrest for PEC sleeping with limited recline

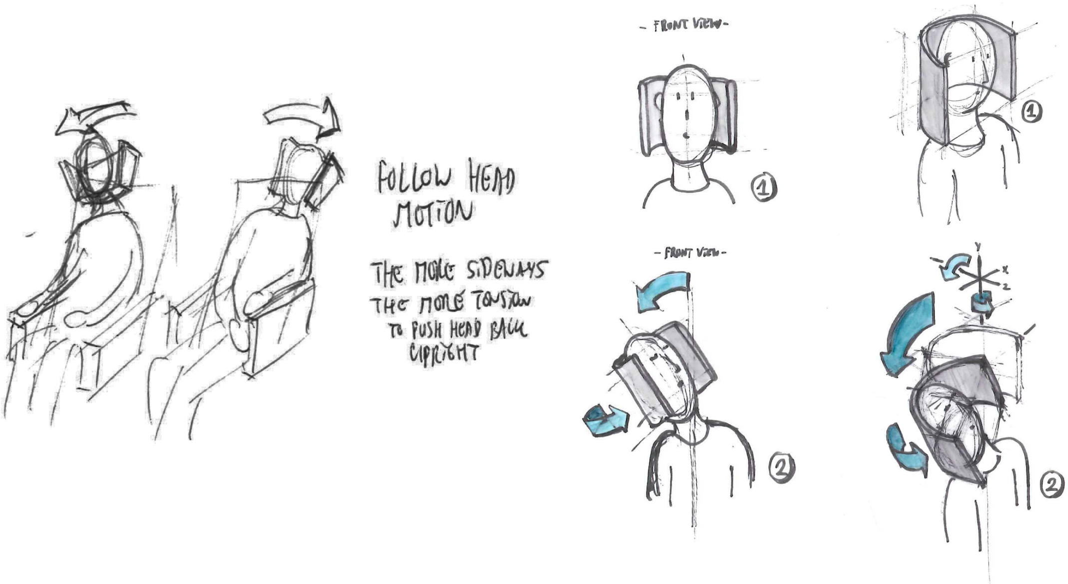


Figure 8.3 | Following headrest for PEC sleeping with limited recline. The headrest allows freedom of movement, which is important during sleep. When sliding too far sideways, the headrest hinges forward over the z-axis, 'catching' the user. This prevents the head to fall down, preventing the the 'falling motion reflex' as described in §5.7.2.

8.1.3 Highly adjustable BC IFE screen

As observed by Smulders et al. (submitted) and Smulders et al. (2016) and Vink et al. (2017) (see §6.5.1), there are multiple issues with the orientation of the IFE screen. To allow a correct posture, the IFE screen centre should be at eye height perpendicular to the line of sight and aligned with the centre of the seat to prevent unbalanced postures.

To accommodate multiple postures (e.g. a lying posture, see Figure 8.5) and serve a larger population (see also Figure 6.14 in §6.5.1), this concept allows the IFE screen to move up and down and to adjust the angle (see Figure 8.4). Such a movement can be realised by a slider and a hinge mechanism. In some new generation BC seats the IFE screen is 'stored' in a compartment in the shell of the seat in front, where it can be folded out. It is important here that the hinge and arm are designed as such that the centre of the screen is aligned with the centre of the seat when folded out fully.

To summarise all features:

- Height adjustable, allowing the centre of the screen at eye height.
- Angle adjustable, allowing the total population (e.g. >P95 male, <P5 female) to make use of the IFE screen without glare, and providing posture alternation (e.g. lying flat).
- Centre of screen aligned with centre of seat (to prevent unbalanced posture).

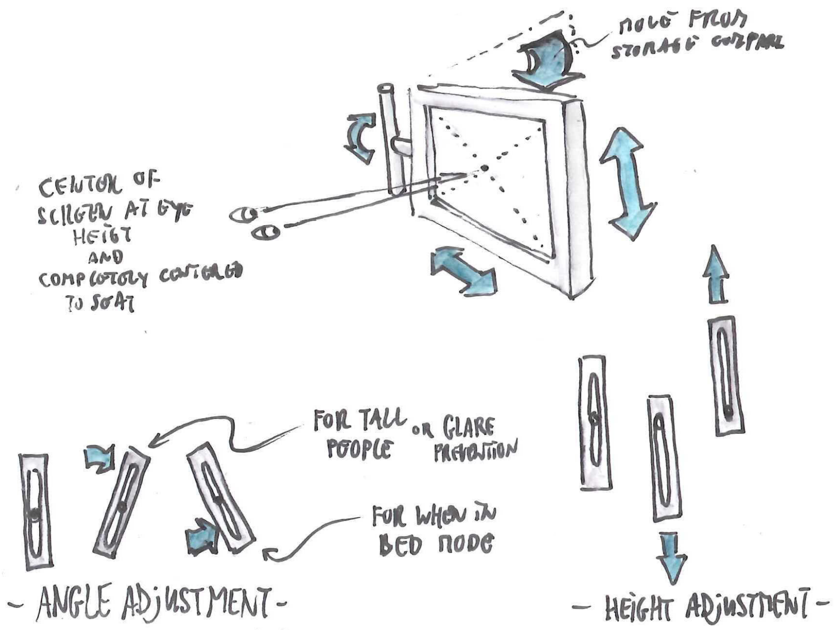


Figure 8.4 | Highly adjustable BC IFE screen for proper view. Height adjustment to meet different body lenghts. Angle adjustment to meet different postures (e.g. see Figure 8.5 and Figure 8.7), adjusting for glare or for very tall passengers.

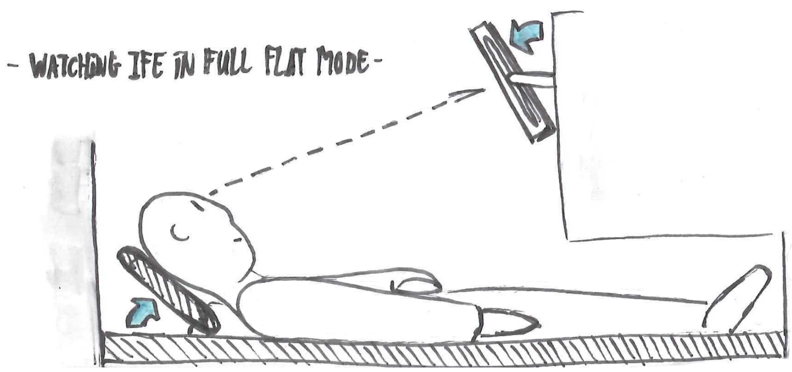


Figure 8.5 | Highly adjustability allows facilitating different postures, such as a full flat lateral posture.

8.1.4 Self-adjusting PEC IFE screen

The best way to watch IFE is by having the screen center on eye height. Current IFE's do not support this for different height of people (see Figure 6.14 in §6.5.1). Additionally, when someone in front reclines their seat, the IFE screen on the backrest gets angled and lowered (see Figure 6.15 in §6.5.1), resulting in improper view making passengers adopt unpleasant postures. When the user reclines their own seat, the viewing height and angle in relation to the IFE changes (see Figure 6.16 in §6.5.1), again resulting in improper view. Current solutions only allow limited pivoting of the IFE screen forward by a hinge, but only to compensate inclination of the seat it is attached to. It does not allow height adjustability for different length of people or compensate the lost height when the seat in front reclines. Passengers now have to adjust their posture (e.g. bending head forward, thereby putting extra tension on trapezius muscle which is uncomfortable) to compensate for the limitations given by the current system.

A mechanism allows the IFE screen to not only pivot forward and backwards, but also to move up and down, allows the IFE screen to meet eye height for viewing comfort and compensate for when the seat in front reclines, which the former the system does not allow. In addition, height and angle adjustment can be done automatically by a mechanism when the seat in front reclines, keeping the IFE screen level at the – by the user – originally set height (e.g. on eye level) (see Figure 8.6). A pulley and scissor hinge my form an appropriate mechanism, but further exploration on mechanism design is required.

To summarise all features:

- Automatic mechanical adjustment of the IFE screen height and orientation, when the seat in front reclines. This minimises the disturbance caused by other passenger (limiting annoyance) and add to the premium feeling of PEC in contrast to EC where (limited) manual adjustment is required.
- Possibility to adjust screen height and angle, to facilitate a better posture and serve a bigger population.

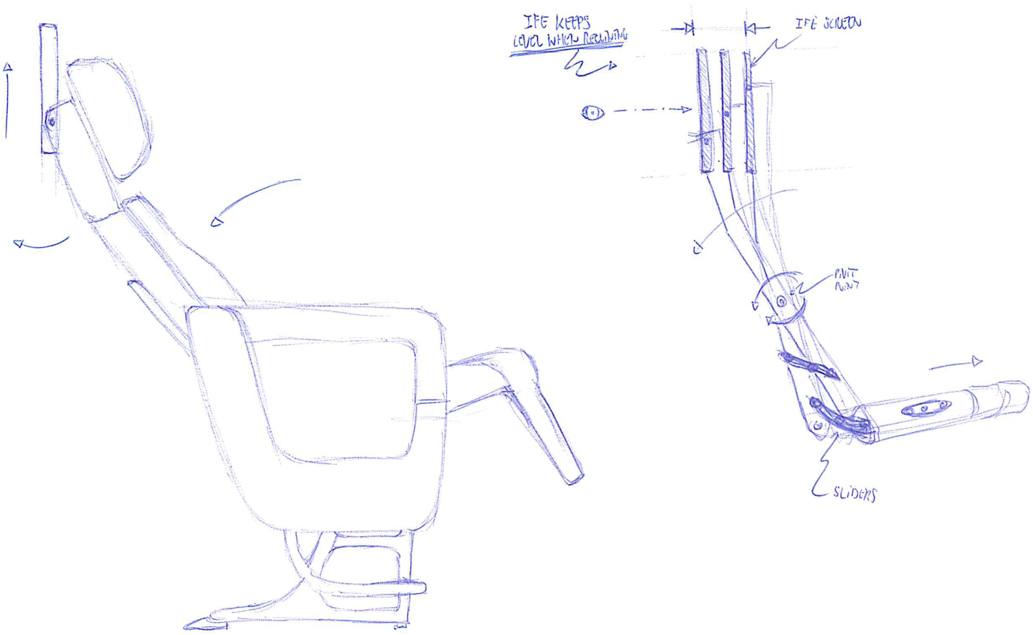


Figure 8.6 | Self-adjusting PEC IFE screen. A mechanism (e.g. located in the back of the backrest) keeps the IFE screen level on eye height when the seat in front reclines. The backrest reclines backwards, moving down and forward (see left image). The mechanism (see right image) compensates this movement by moving up the IFE screen and increases its angle; the screen only moves longitudinal (backward, towards the passenger behind).

8.1.5 **Forward tilting headrest for better IFE experience**

As watching IFE in a slouched posture is preferred, prolonged neck flexion or eye deromsumversion are required (as described in chapter 6). To lower the load on the musculoskeletal system and increase the comfort experience, this concept provides head support. The headrest articulates forward over a simple torque hinge, which is commonly used in aircraft headrests for side flaps. The hinge is cheap, reliable and certified for aviation use, making it a relative easy implementable concept. Such a headrest mechanism may also be used when watching IFE in full flat mode (see Figure 8.5). It is advised to combine this feature with adjustability of the height of the screen (see §8.1.3), to allow a straight view (perpendicular) to the centre of the IFE screen.

To summarise all features:

- Facilitating support for slouched sitting when prolonged watching IFE screen.

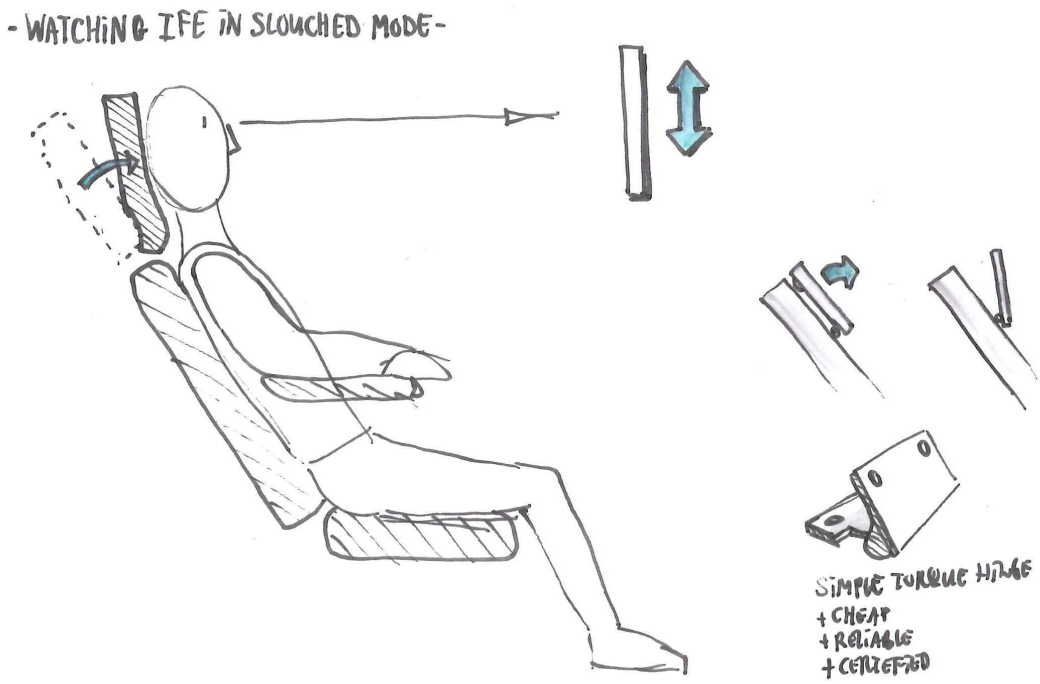


Figure 8.7 | Forward tilting headrest for better IFE experience

8.2 Brief elaboration on sleeping in PEC with limited recline

As sleeping with a limited recline is one of the most challenging problems, providing a practical and pleasant solution can be very beneficial for the PEC passenger and thus very interesting for airliners. It would improve differentiation and thus price justification of PEC over EC. As the 'following headrest for PEC sleeping with limited recline' allows natural movement of and providing support to the head by a unique movement, this design was further explored. The shape was determined through paper prototyping and the mechanism design by designing and simulating articulation in SolidWorks.

8.2.1 Paper prototyping of folding headrest

With cardboard a paper prototype was made of the headrest described in §8.1.2.1, exploring the effectiveness of the mechanism (see Figure 8.8). Although the mechanism to some extend works, it is very big. Furhter exploration and optimisation is needed. Inspiration could be derived from the other paper prototype, e.g. for integrating the chin support.

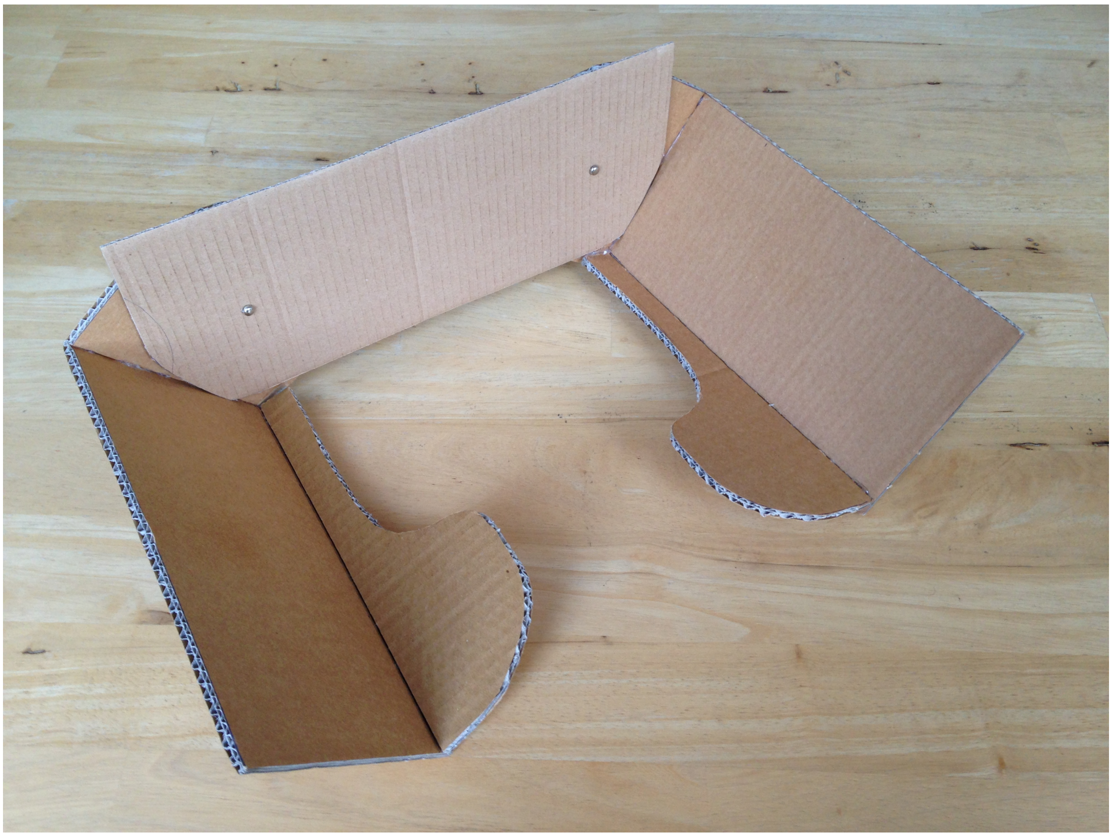


Figure 8.8 | Paper prototype of static headrest with side flaps folded out and downward

8.2.2 Paper prototyping of following headrest

With foam and cardboard a prototype was made to find appropriate shape and cushioning for the following headrest described in §1.1.1.1 (see Figure 8.9). The headrest is in a V-shape, which with the cheek support flaps at the bottom form a kind of concave surface – inspired on the palm of the hand – where the head can rest in (see Figure 8.10). Firmer foam was placed at the cheek support flaps and the upper part at the top head area to carry the head load. Soft foam was placed at the cheek areas, as these are more sensitive. The back features a soft curved neck support and a more firm head support above (§4.5). As not everybody likes neck support (§4.5), a sliding mechanism was prototyped to allow adjustment (see Figure 8.11).

The shape and padding choice feel good and show promise in personal testing. It seems to provide adequate and comfortable support when simulating movement by hand. Further testing of the comfort of the shape and padding and its effectiveness in head support on subjects is advised.

Figure 8.9 | Paper prototype of headrest

Figure 8.10 | Headrest in use

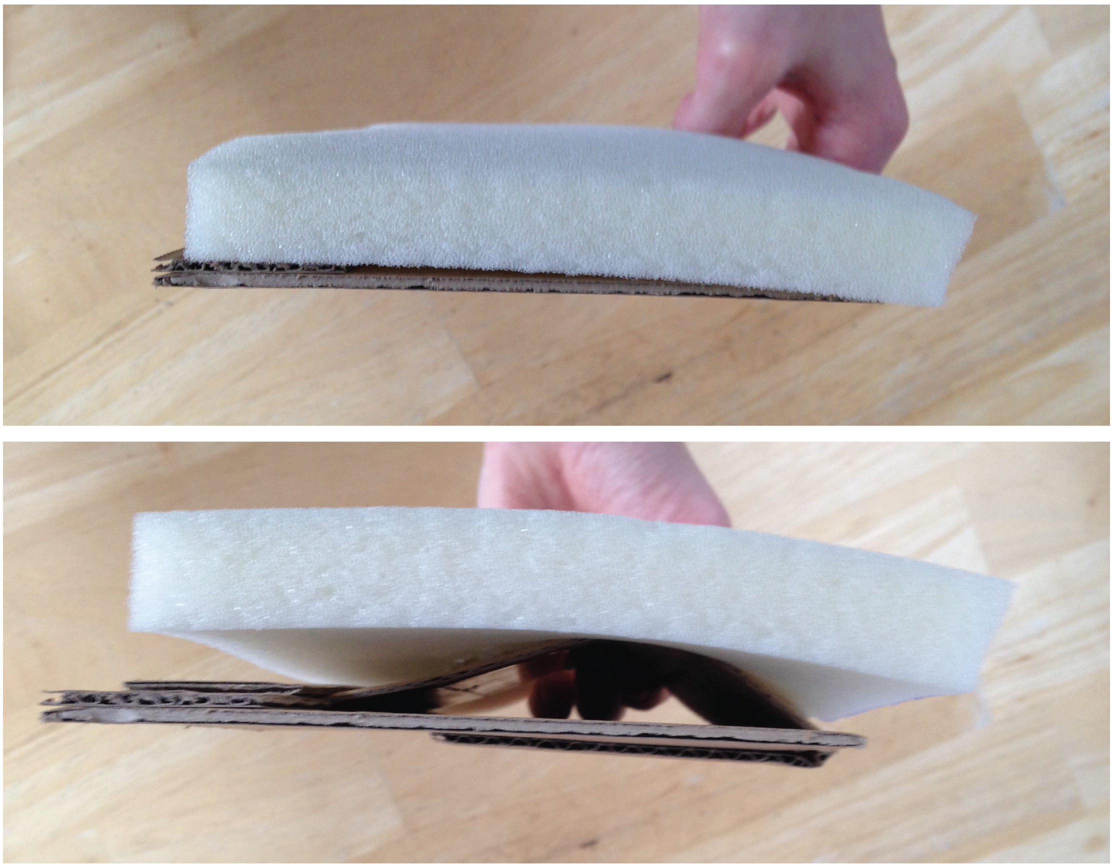


Figure 8.11 | Adjustable neck support mechanism

8.2.3 Mechanism design in SolidWorks of following headrest

As the ‘following headrest for PEC sleeping with limited recline’ design showed promise, the actual mechanism was further explored. Three mechanism ideas were selected: A) a turning arm with a diagonal rotation point B) a linkage system with two ball joint connected rods and two rotation hinges and C) a double curved slider track. Each his it's own benefits and shortcomings. Concept A and B were simulated in SolidWorks, where with trial and error measurements and workings of the design were explored by making use of a 3D scan of the head in the required angles (see Figure 8.14).

Mechanism A is a turning arm with a diagonal rotation point allowing it to turn over the Y and Z axis (see Figure 8.13). The length of the arm and the angle of the rotational point are the main parameters determining the movement. As shown in Figure 8.13 the initial design is compact, but does not articulate properly, as it does not swing out far enough. By playing with the parameters (angle and arm length) it was found out that the arm needed to be extended (see fig. 8.14) to follow correctly the required movement. However, such a large arm requires relatively a lot of space in the backrest, although in PEC there is more room for that. Another issue is the moment force it creates on the hinge as wrong usage and impact may damage the mechanism. Increasing the strength of pars would likely results in a heavier seat. The benefit of this mechanism however is that it is relative simple, but optimisation in strength (reliability) and volume are required.

Mechanism B (see Figure 8.15) consists of a linkage system, with two ball joint connected rods and two rotation hinges, rotating over the Z and Y-axis. The rods guide the movement, where the rotating hinges mainly carry the load. The benefit of this mechanism is that it is more compact, but the complexity may make it less reliable and costly. Also the close proximity of moving parts pose risk for hair and fingers to get stuck in between or seriously injured, which is a major safety issue. The use of a dress cover may prevent hair to get stuck, but for fingers another solution need to be found. Furhter development is thus required, with a focus on the safety, but also making the mechanism less complex, as it now contains six moving parts.

Mechanism C is a double curved slider track to articulate the headrest (see Figure 8.16). Although it has potential, sliders are vulnerable mechanism that can easily be damaged. Therefore aircraft seat engineers are reluctant to use them. Also required play and the increase of play due to wear make them noisy, which is not ideal as it is used in close proximity to the user's ears. Another issue is the complexity of movement, as the track is double curved. The slider wheels could be placed on a ball bearing (see bottom Figure 8.16), giving it the freedom to articulate in each direction, allowing it to follow the track. Further optimisation is required.

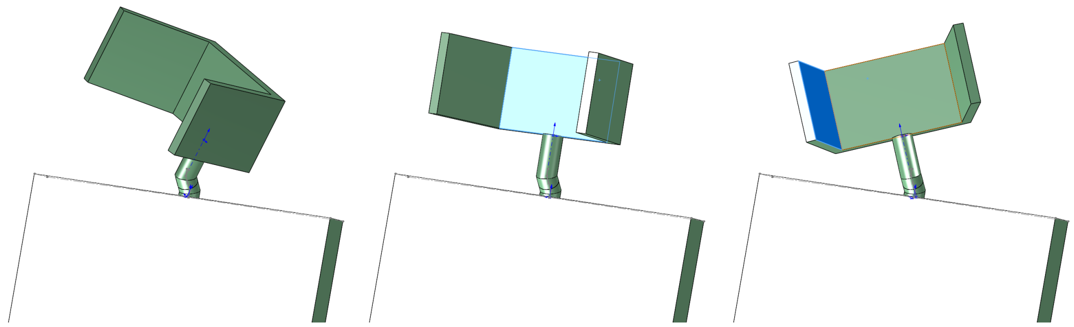


Figure 8.14 | Following headrest mechanism A. The headrest turns over a diagonal placed rotational hinge. The benefit is simplicity and durability. However, the length of the moving arm should be quite tall to facilitate the proper movement, as demonstrated in Figure 8.14.

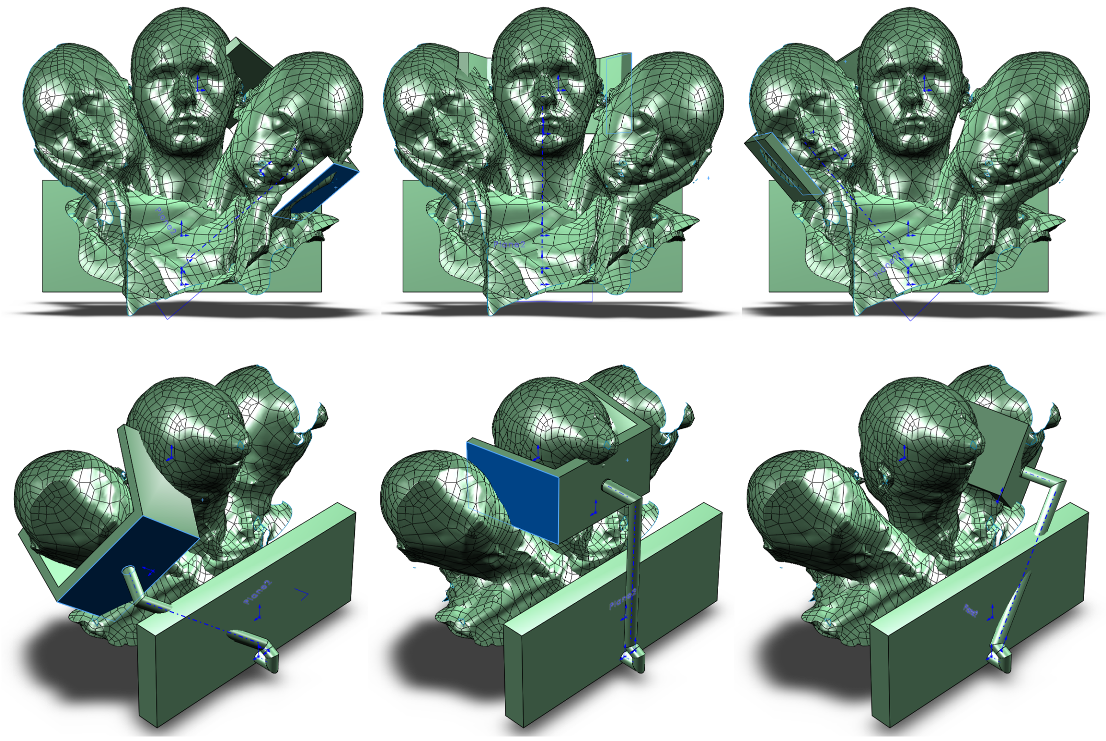


Figure 8.15 | Following headrest mechanism A following the required movement. Experimental study based on 3D scan of the head positions. As can seen below, the arm needs to be quite tall, requiring a lot of room to move and counteracting the force with e.g. a torque spring becomes more difficult as the moment force on the spring can be expected to be quite big.

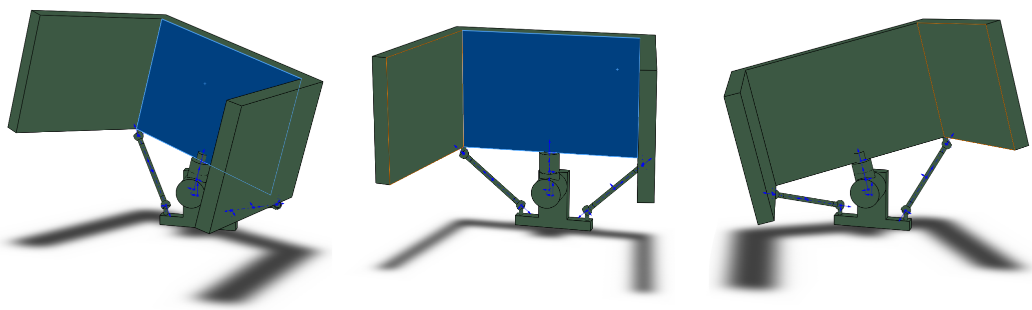


Figure 8.16 | Following headrest mechanism B. The headrest turns over a Z and Y shaft, guided by two rods fixated with four ball joints to make the required movement. The benefit is the compactness. However, the mechanism is complex, making it vulnerable for damaging and costly in maintenance.

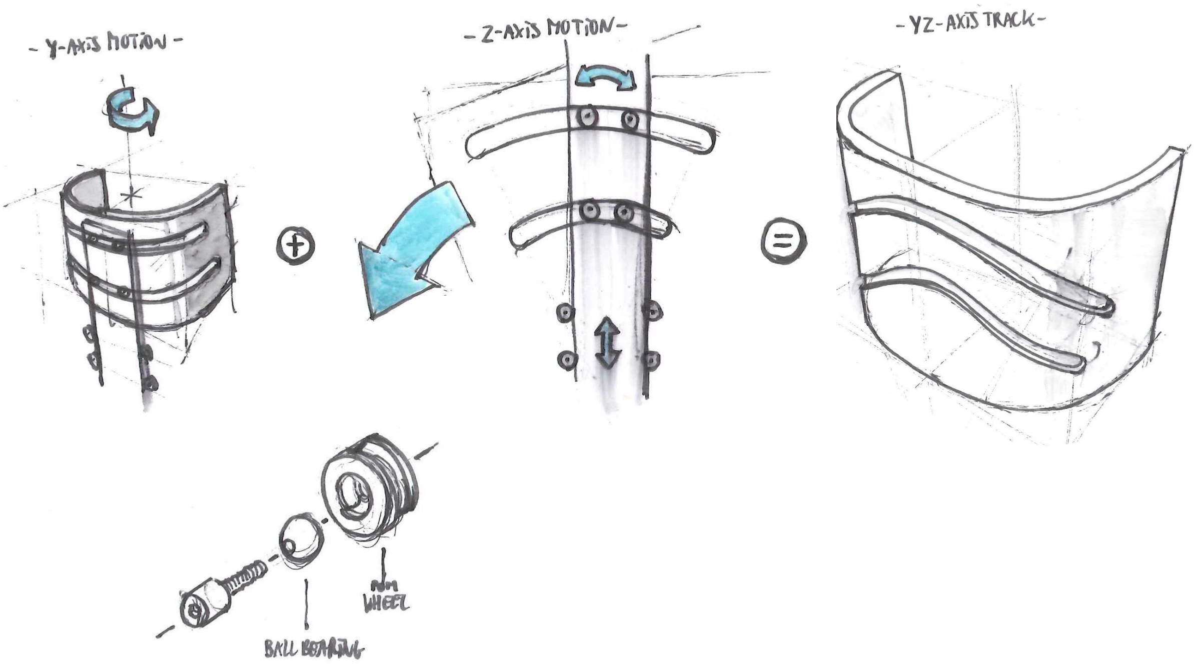


Figure 8.15 | Following head mechanism C. Double curved slider over two tracks (right), translating the headrest over the central headrest connection. By combining the rotational translation over the Y-axis (left) and Z-axis (middle), one gets the YZ-translation which 'catches' the head. A bal-joint based slider wheel is required (bottom) to allow 'driving' over the double curved track.

8.3 Concept evaluation

All concepts show potential. The most interesting would be the solution for sleep in PEC, as sleeping with limited recline poses serious challenges to sleeping comfort and efficiency. A solution may be a disruptor in the PEC cabin, as passengers will expect the better sleep experience. It is thus an interesting tool for airliners to differentiate themselves from their competition.

Althoug the ‘following headrest for PEC sleeping with limited recline’ show promise, none of the mechanisms satisfies current safety and reliability requirements. Further exploration and optimisation is thus required to make a reliable and safe mechanism that makes the required movement to ‘catch’ the head. All concepts also require height adjustment options, to facilitate a larger population. It may be that a complete new mechanism would do the job better. These mechanism concepts may form a starting point for further exploration and development.

In addition attention needs to be given to hygiene, e.g. trough the addition of an antimacassar at contact area's with the head and face.

Chapter 9 **Page**

9 Evaluation and conclusion

9.1 Process evaluation

Due to many changes along the project due to external factors I had to be flexible. For example, the intended collaboration with ZSUS did not go as planned due to the unexpected forced leave of my company mentor, dr. Schultheis, director of Human Factors and Ergonomics. The Human Factors and Ergonomics team did their best to support the graduate interns, including me. But the lack of interest, attention and guidance from the management, the bad work atmosphere at ZSUS, and the loss of research and prototype budgets did not help the project. Also the forced transition from the original project on long-haul BC to domestic BC was not beneficial, as the project focus of watching IFE and sleep did not fit the context of domestic BC. Domestic BC is mainly short to medium haul day flights, and thus BCP's are more interested in activities such as working. Also the transition form full-flat BC to limited recline PEC can still be seen in the thesis. For example, extensive research has been carried out into sleeping postures, where this information has limited use in the final designs. It however has led to new knowledge, which can be used in the industry.

Although not originally planned, I have put the emphasised of this project on scientific research, both by conducting literature studies, lab studies on subjects and analysis in the field. Because of this, attention to design, embodiment design and prototyping were limited. Personally, I find this pity, especially since I enjoy CAD optimisation and making prototypes. When looking back, it would have been better to focus earlier in the process on one context, one subject and one design. This would have given more direction and more time to spend on embodiment design and prototyping. Doing literature and EMG studies was really learning on the job, finding out what works and what does not. In the future for example I would like to conduct my literature research more structured, making summaries of each paper and archive papers according to author and subject. Another thing I would do differently is visualising during the process. Where this time I decided to finish my texts first, with the idea to have tackled the hardest thing first and would have time to spend more efficiently on visualisations and layout in the end. However, I really missed the verity of graphic design alongside my project and in the end it did not safe any time at al.

However, I am very pleased with the quality of work and research. I think I have added new knowledge and have been able to give recommendations to the industry and for further research. And as strange it may sound, I am very proud of Table 5.4, which is – to my knowledge – the most comprehensive literature review of human sleeping postures. Furthermore, the selected concepts and ideas show genuine potential for improving comfort in premium cabins for sleep and watching IFE. As such the head support for watching IFE has been explored for patenting by ZSFR. The final graduation product became not a final design, but the publication of a journal paper (see Appendix C). The first version of this paper was first presented at the first International Comfort Congress (ICC) in Salerno, Italy, as a conference paper (see Appendix B). The technical committee of the ICC selected this paper for submission in Elsevier's Applied Ergonomics. After further elaboration on the paper, it now has been submitted to be peer reviewed.

9.2 Conclusion

This master thesis shows that through headrest design comfort of premium aircraft passengers can be improved for watching IFE and sleeping with limited recline. Headrest design is less applicable on BC full-flat sleep, where a focus on bed-seat mattress design and control features is more relevant. Aircraft seat manufacturers are therefore advised to further research and develop proposed headrest designs, as current headrest are insufficient and underexposed in seat design.

9.3 Recommendations for further research and development

9.3.1 Automated pressure adjustment based on posture and anthropometrics

As discussed in §5.6.2 a different pressure distribution per area is required for different activities (such as sitting and sleeping) and different people (tall, small, slim, big). In the case of providing a full flat bed within the same seat, this pressure distribution needs to be adjusted. As this was out of scope, no further elaboration was made on this matter. However, automated adjustment of pressure distribution according to the posture (and thus activity) and anthropometrics could provide an improvement in comfort and a new generation of premium aircraft seats. Further research is recommended on this matter, exploring the possibility to develop such a highly adjustable seat.

9.3.2 Possibilities for minimising jet-lag effects trough cabin design

As discussed in §5.3.4, it might be beneficial to passenger comfort and travel efficiency to exploring ways to minimise jet-lag effects, e.g. trough pre-adjusting the circadian rhythm of passengers trough light intensity and colour, temperature adjustment and activity shifting (e.g. meal time).

9.3.3 Upright sleeping in transit

As discussed in §5.7.2, upright poses challenges to falling asleep, keeping asleep and sleep quality. Research on sleeping in minimal recline is advised, e.g. exploring and testing designs from this graduation thesis, but also the minimal required backrest inclination. It is advised to explore the idea of the 'falling motion effect' in more detail, as it may be one of the major contributors to ineffective sleep in PEC and EC aircraft seats.

9.3.4 Neutral head position and headrest design

As discussed in §6.7 (see also Appendix C), further research is also advised on the ideal angle of support by and the long-term effects of the use of a headrest when watching IFE in a slouched posture on comfort, discomfort and fatigue, as in real life passengers will watch IFE for a prolonged amount of time during long-haul flights (e.g. watching multiple movies).

9.3.5 IFE ergonomics: recommendations for IFE in the aircraft

As discussed in §5.1 and §5.8, screen recommendations are based on VDU, computer and tablet use. However, the context of IFE in the aircraft is different. Therefore research on IFE screen orientation, size and distance, based on literature and new experiments with screen size preferences, distances and angles in both EC and BC is recommended to give adequate recommendations.

10

10 References

The following states all references from this thesis, including those in Appendix D till J. References of Appendix A, B and C can be found in those papers respectively.

A Adams, J. (2012). Who weighs the aussie average? *Marie Claire (Australia),* pp. 52-56. Retrieved from nicolepartridge.com/wp-content/uploads/2012/05/MC05_FEAT_70kg.pdf

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.

Agrawal, K., & Chauhan, N. (2012). Pressure ulcers: Back to the basics. *Indian Journal of Plastic Surgery, 45*(2), 244.

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.

Akkerman, S. (2016). *Thesis: Improving Boarding Efficiency And Experience*. Retrieved from resolver.tudelft.nl/uuid:91798ddd-ae7a-410e-8873-b14278dd1ae0

Alamdari, F. (1999). Airline in-flight entertainment: the passengers' perspective. *Journal of Air Transport Management, 5*(4), 203-209.

Ambrogio, N., Cuttiford, J., Lineker, S., & Li, L. (1998). A comparison of three types of neck support in fibromyalgia patients. *Arthritis & Rheumatism, 11*(5), 405-410.

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.

Anonymous (2016).

Ansari, M. W., & Nadeem, A. (2016). Atlas of Ocular Anatomy.

Ardito, M., Gunetti, M., & Visca, M. (1996). Influence of display parameters on perceived HDTV quality. *IEEE transactions on consumer electronics, 42*(1), 145-155.

Associated Press. (1987). Hanson Trust to acquire Kidde for $1.6 billion and stock rights. Retrieved from http://www.apnewsarchive.com/1987/Hanson-Trust-To-Acquire-Kidde-For-$1-6-Billion-And-Stock-Rights/id-74081d6a27e72273641b85363686d314

Balcombe, K., Fraser, I., & Harris, L. (2009). Consumer willingness to pay for in-flight service and comfort levels: A choice experiment. *Journal of Air Transport Management, 15*(5), 221-226.

Balkin, T. J., O'Donnell, V. M., Kamimori, G. H., Redmond, D. P., & Belenky, G. (1989). Administration of triazolam prior to recovery sleep: effects on sleep architecture, subsequent alertness and performance. *Psychopharmacology, 99*(4), 526-531.

B Basner, M., Glatz, C., Griefahn, B., Penzel, T., & Samel, A. (2008). Aircraft noise: effects on macro-and microstructure of sleep. *Sleep medicine, 9*(4), 382-387.

Bauer, W., & Wittig, T. (1998). Influence of screen and copy holder positions on head posture, muscle activity and user judgement. *Applied ergonomics, 29*(3), 185-192.

BBC News. (2008). Silverjet calls in administrators. *BBC*. Retrieved from news.bbc.co.uk/2/hi/business/7427056.stm

BC FA. (2015) *Interview #3: Two stripe CA and four stripe purser/Interviewer: M. Smulders*.

Berghman, K., Kane, J. A., Krishna, K., Koenraads, M., Carter, T. K., & Smulders, M. (2014). *Zodiac Azure seat design: designing a business class seat based on the human contour.* (Confidential AED report for Zodiac Aerospace), Delft University of Technology, Delft.

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.

Blake, M. J. F. (1967). Relationship between Circadian Rhythm of Body Temperature and Introversion-Extraversion. *Nature, 215*(5103), 896-&. doi:DOI 10.1038/215896a0

Bland, B. (2008). Eos Airlines files for bankruptcy. *The Telegraph*. Retrieved from telegraph.co.uk/finance/newsbysector/transport/2789077/Eos-Airlines-files-for-bankruptcy.html

Blok, M., Vink, P., & Kamp, I. (2007). Comfortabel vliegen: comfort van het vliegtuiginterieur door de ogen van de gebruiker.

Boeder, P. (1961). The co-operation of extraocular muscles. *American journal of ophthalmology, 51*(3), 469-481.

Bouwens, J. M. A. (2017). Passenger comfort goes beyond antropometrics: How environmental factors in the aircraft cabin interior influence comfort experience. *Tijdschrift voor Human Factors, 42*(4), 6-9.

Braggs, S. (2017a). Air travel in the 50s. Retrieved from retrowow.co.uk/transport/50s/Air_travel_50s.html

Braggs, S. (2017b). Air travel in the 60s. Retrieved from retrowow.co.uk/transport/60s/air_travel/air_travel_60s.html

Braggs, S. (2017c). History of business class flights. Retrieved from retrowow.co.uk/transport/air_travel/business_class.html

Brauer, K. (2004). *Convenience, comfort and costs.* Paper presented at the Aircraft Interior Expo, Hamburg.

Braun, B. L., & Amundson, L. R. (1989). Quantitative assessment of head and shoulder posture. *Archives of physical medicine and rehabilitation, 70*(4), 322-329.

British Airways. (2016). Explore our past: 1990-1999. Retrieved from http://www.britishairways.com/en-gb/information/about-ba/history-and-heritage/explore-our-past/1990-1999

British Airways. (2017). Plan your journey (ticket booking). Retrieved from britishairways.com/travel/fx/public/en_nl

Bronkhorst, R., & Krause, F. (2005). Comfort and Design: Principles and Good Practice. In P. Vink (Ed.), *Comfort and Design: Principles and Good Practice* (pp. 155-168). Boca Raton: CRC Press.

Brown, C., & Schaum, D. (1980). User-adjusted VDU parameters. *Ergonomic aspects of visual display terminals*, 195-200.

Burgess-Limerick, R., Plooy, A., & Mon-Williams, M. (1998). The effect of vertical visual target location on head and neck posture. *Contemporary ergonomics*, 123-129.

C

Candas, V., Libert, J., & Muzet, A. (1982). Heating and cooling stimulations during SWS and REM sleep in man. *Journal of Thermal Biology, 7*(3), 155-158.

Candas, V., Libert, J., Vogt, J., Ehrhart, J., & Muzet, A. (1979). Body temperature during sleep under different thermal conditions. *Indoor Climate, Effect on Human Comfort, Performance and health*, 763-776.

Carskadon, M. A., & Dement, W. C. (2017). Normal human sleep: an overview. *Principles and practice of sleep medicine, 6th edition*, 13-23.

Cavallero, C., & Versace, F. (2003). Stage at awakening, sleep inertia and performance. *Sleep Research Online, 5*(3), 89-97.

Clark, J. (2014). The Past, Present, and Future of Business Class seat design.

Clark, T. (2016, April 5th). Crystal Cabin Award ceremony, Hamburg.

Clarkson, J. (2008). Human capability and product design *Product experience* (pp. 165-198): Elsevier.

Claussen, J., & O'Higgins, E. (2010). Competing on value: Perspectives on business class aviation. *Journal of Air Transport Management, 16*(4), 202-208.

Clayton, E., & Hilz, A. (2015). 2015 Aviation Trends. Retrieved from strategyand.pwc.com/perspectives/2015-aviation-trends

Coelho, D. A., & Dahlman, S. (2012). Articulation at shoulder level–A pilot experimental study on car seat comfort. *Applied ergonomics, 43*(1), 27-37.

Coenen, A. M. L. (2006). De slaap en het bed - Een psychobiologische beschouwing.pdf>. *Medische Antropologie, 18*(1), 133-148.

Coenen, A. M. L. (2011). *Sleep, the bedroom and the bed.* Paper presented at the NSWO.

Coenen, A. M. L., & Kolff, M. (2011). *Body postures in sleep*. Paper presented at the NSWO.

Corlett, E. (1999). Are you sitting comfortably? *International Journal of Industrial Ergonomics, 24*(1), 7-12.

Crean, D. (2015). Stages of Sleep. Retrieved from www.sleepdex.org/stages.htm

Cui, W., Ouyang, Q., & Zhu, Y. (2014). Field study of thermal environment spatial distribution and passenger local thermal comfort in aircraft cabin. *Building and Environment, 80*, 213-220.

D Dalassio, D. J. (1980). *Wolff's Headache and Other Head Pain*. Oxford: Oxford University Press.

Danard, J. (1978). The changing world of business travel. *The Financial Post,* pp. 1-2. Retrieved from news.google.com/newspapers?id=FGM_AAAAIBAJ&sjid=sFMMAAAAIBAJ&pg=3911%2C2956115

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.

de Koninck, J., Lorrain, D., & Gagnon, P. (1992). Sleep positions and position shifts in five age groups: an ontogenetic picture. *Sleep: Journal of Sleep Research & Sleep Medicine*.

de Korte, E. M., Spiekman, M., Hoes-van Oeffelen, L., van der Zande, B., Vissenberg, G., Huiskes, G., & Kuijt-Evers, L. F. (2015). Personal environmental control: Effects of pre-set conditions for heating and lighting on personal settings, task performance and comfort experience. *Building and Environment, 86*, 166-176.

De Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of biomechanics, 29*(9), 1223-1230.

Defloor, T. (2000). The effect of position and mattress on interface pressure. *Applied Nursing Research, 13*(1), 2-11.

Delleman, N. J., Haslegrave, C. M., & Chaffin, D. B. (2004). *Working Postures and Movements*: CRC Press.

Denstadli, J. M. (2004). Impacts of videoconferencing on business travel: the Norwegian experience. *Journal of Air Transport Management, 10*(6), 371-376.

Derudder, B., Beaverstock, J. V., Faulconbridge, J. R., Storme, T., & Witlox, F. (2011). You are the way you fly: on the association between business travel and business class travel. *Journal of Transport Geography, 19*(4), 997-1000.

Dewasmes, G., Telliez, F., & Muzet, A. (2000). Effects of a nocturnal environment perceived as warm on subsequent daytime sleep in humans. *Sleep, 23*(3), 409-413.

Di Nisi, J., Ehrhart, J., Galeou, M., & Libert, J. (1989). Influence of repeated passive body heating on subsequent night sleep in humans. *European journal of applied physiology and occupational physiology, 59*(1), 138-145.

Dierikx, M. (2008). *Clipping the Clouds: How Air Travel Changed the World*: Praeger Publishers.

Dijk, D.-J. (2009) *Why do Buddhist monks sleep upright?/Interviewer: BBC*. BBC News.

Dijk, D.-J., Brunner, D. P., & Borbély, A. A. (1991). EEG power density during recovery sleep in the morning. *Electroencephalography and clinical neurophysiology, 78*(3), 203-214.

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.

Drake, C. L., & Wright, K. (2011). Shift work, shift-work disorder, and jet lag. *Principles and practice of sleep medicine, 6th edition*, 784-798.

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.

Dreyfuss, H. (1967). *Designing for people*. New York: Paragraphic Books.

Durston, J. (2013). Keep your wider seats - what planes need are better headrests. *Cable News Network*. Retrieved from edition.cnn.com/travel/article/planes-need-better-headrests/index.html

E Eisenbrand, J. (2004). "More legroom please": A historical survey of the aircraft seat *Airworld: Design and Architecture for Air Travel* (pp. 124-142). Germany: Vitra Design Museum.

Ellegast, R. P., Kraft, K., Groenesteijn, L., Krause, F., Berger, H., & Vink, P. (2012). Comparison of four specific dynamic office chairs with a conventional office chair: impact upon muscle activation, physical activity and posture. *Applied ergonomics, 43*(2), 296-307.

Emery, R. B. (2017). *Seat Psychology*. International Comfort Conference. Salerno, Italy.

Enck, P., Walten, T., & Traue, H. C. (1999). Associations between back pain, quality of sleep and quality of mattresses. Double-blind pilot study with hotel guests. *Schmerz, 13*(3), 205-207. doi:DOI 10.1007/s004820050200

Enoch, J. M. (1959). Effect of the size of a complex display upon visual search. *JOSA, 49*(3), 280-285.

F

Farine, D., & Seaward, P. G. (2007). When it comes to pregnant women sleeping, is left right? *Journal of Obstetrics and Gynaecology Canada, 29*(10), 841-842.

Fickling, D. (2014). A Business-Class Seat That Lets Flyers Sleep From Takeoff to Landing. Retrieved from http://www.bloomberg.com/bw/articles/2014-10-30/a-business-class-seat-that-lets-flyers-sleep-from-takeoff-to-landing

Filho, N. M., Coutinho, E. S., & e Silva, G. A. (2015). Association between home posture habits and low back pain in high school adolescents. *European Spine Journal, 24*(3), 425-433.

Flagg, M. (1992). British Owner Sells Weber Aircraft for $85 Million : Transaction: The cash buyer of the airliner components maker is Air Cruisers Co. of New Jersey, which is likely to expand its market. *Los Angeles Times*. Retrieved from http://articles.latimes.com/1992-10-07/business/fi-673_1_weber-aircraft-inc

Flynn-Evans, E. E., Caddick, Z. A., Gregory, K., & Center, J. S. (2016). *Sleep Environment Recommendations for Future Spaceflight Vehicles.* NASA, Houston, Texas, USA. Retrieved from ston.jsc.nasa.gov/collections/TRS/_techrep/TM-2016-219282.pdf

Foreign Investment Promotion Agency Tunisia. (2016, 11-16-2016). Zodiac Automotive Tunisia / Zodiac Seats Tunisia. Retrieved from www.investintunisia.tn/En/success-stories_113_114_D48#.WCxU9iPhBcw

Forgatsch, O., & Lohrmann, J. (2016). [RECARO presentation and discussion].

Franz, M., Durt, A., Zenk, R., & Desmet, P. M. (2012). Comfort effects of a new car headrest with neck support. *Appl Ergon, 43*(2), 336-343. doi:10.1016/j.apergo.2011.06.009

Fuller, P. M., Gooley, J. J., & Saper, C. B. (2006). Neurobiology of the sleep-wake cycle: sleep architecture, circadian regulation, and regulatory feedback. *J Biol Rhythms, 21*(6), 482-493. doi:10.1177/0748730406294627

G

Garcia, M. (2014a). Fresh Approach. *Aircraft Interiors International Magazine, March 2014,* 58-64.

Garcia, M. (2014b). How In-Flight Entertainment Saved JetBlue. Retrieved from skift.com/2014/05/30/how-in-flight-entertainment-saved-jetblue/

Garcia, M. (2016). Calculating the Cost of a Better Airline Cabin for All. *Skift.* Retrieved from skift.com/2016/01/13/calculating-the-cost-of-a-better-airline-cabin-for-all/

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

Gausewitz, C. H. (1964). *Space for audio-visual large group instructions*: Madison: University of Wisconsin.

Goldsmith, R., & Hampton, I. (1968). Nocturnal microclimate of man. *The Journal of physiology, 194*(1), 32P.

Goossens, R. H. M. (2016, April 19th). [Discussion head support for watching IFE and sleep].

Goossens, R. H. M., Snijders, C. J., Roelofs, G. Y., & Buchem, F. V. (2003). Free shoulder space requirements in the design of high backrests. *Ergonomics, 46*(5), 518-530.

Gordon, S. J., & Buettner, P. G. (2009). Age and lateral sleep position: a pilot study. *Internet Journal of Allied Health Sciences and Practice, 7*, 1-5.

Gordon, S. J., Grimmer, K. A., & Trott, P. (2004). Self-reported versus recorded sleep position: an observational study.

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.

Gordon, S. J., Grimmer-Somers, K., & Trott, P. (2009). Pillow use: the behaviour of cervical pain, sleep quality and pillow comfort in side sleepers. *Manual therapy, 14*(6), 671-678.

Gori, S., Ficca, G., Giganti, F., Di Nasso, I., Murri, L., & Salzarulo, P. (2004). Body movements during night sleep in healthy elderly subjects and their relationships with sleep stages. *Brain Res Bull, 63*(5), 393-397. doi:10.1016/j.brainresbull.2003.12.012

Gracovetsky, S., & Farfan, H. (1986). The optimum spine. *Spine, 11*(6), 543-573.

Grandjean, E., Hünting, W., & Pidermann, M. (1983). VDT workstation design: Preferred settings and their effects. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 25*(2), 161-175.

Greghi, F. M., Rossi, N. T., Souza, G. B., & Menegon, L. N. (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 Suppl 1*, 55-60. doi:10.3233/WOR-2012-0135-55

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.

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.

Groenesteijn, L., Vink, P., de Looze, M., & 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.

H Haex, B. (2005). *Back and bed: Ergonomic aspects of sleeping.*: Boca Raton: CRC Press.

Haex, B. (2017, 30th of May). [Question on sleeping positions from Back and Bed: Ergonomic Aspects of Sleeping (2005)].

Harrison, D. D., Harrison, S. O., Croft, A. C., Harrison, D. E., & Troyanovich, S. J. (2000). Sitting biomechanics, part II: optimal car driver's seat and optimal driver's spinal model. *Journal of manipulative and physiological therapeutics, 23*(1), 37-47.

Hartung, J. (2006). *Objektivierung des statischen Sitzkomforts auf Fahrzeugsitzen durch die Kontaktkräfte zwischen Mensch und Sitz.* Technische Universität München.

Haskell, E. H., Palca, J. W., Walker, J. M., Berger, R. J., & Heller, H. C. (1981). The effects of high and low ambient temperatures on human sleep stages. *Electroencephalography and clinical neurophysiology, 51*(5), 494-501.

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.

Hiemstra-van Mastrigt, S. (2015). *Comfortable passenger seats: Recommendations for design and research*. Delft: Delft University of Technology.

Hiller, M. (2016, 24 Maart) *Taking a Seat with Recaro's CEO, Mark Hiller/Interviewer: K. Sehl*. Airline Passenger Experience Association, www.apex.aero.

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.

I IATA. (2012). 2012 IATA Global Passenger Survey Highlights. Retrieved from iata.org/publications/Documents/2012-iata-global-passenger-survey-highlights.pdf

IATA. (2013). 2013 IATA Global Passenger Survey Highlights. Retrieved from iata.org/publications/Documents/global-passenger-survey-2013-highlights.pdf

IATA. (2014). 2014 IATA Global Passenger Survey. Retrieved from iata.org/publications/Documents/2014%20IATA%20Global%20Passenger%20Survey%20Highlights.pdf

IATA. (2015). *2015 IATA Global Passenger Survey.* Paper presented at the 6th World Passenger Symposium Dubai.

IATA. (2016a). 2016 IATA Global Passenger Survey Highlights. Retrieved from iata.org/publications/store/Documents/GPS-2016-Highlights-Final.pdf

IATA. (2016b). *Aircraft Interior Configuration Document (May commonly be called a LOPA)*. Retrieved from faa.gov/about/initiatives/atos/air_carrier/media/2d-16.pdf

IATA. (2016c). IATA by Region. Retrieved from iata.org/about/worldwide/Pages/index.aspx

Iber, C., Ancoli-Israel, S., Chesson, A., & Quan, S. (2007). AASM Manual for the Scoring of Sleep and Associated Events: Rules, Terminology and Technical Specifications. Westchester: American Academy of Sleep Medicine.

J Jaschinkski, W., Heuer, H., & Kylian, H. (1999). A procedure to determine the individually comfortable position of visual displays relative to the eyes. *Ergonomics, 42*(4), 535-549.

Jaschinski-Kruza, W. (1988). Visual strain during VDU work: the effect of viewing distance and dark focus. *Ergonomics, 31*(10), 1449-1465.

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.

Johnson, H., Swan, T., & Weigand, G. (1930). In what positions do healthy people sleep? *Journal of the American Medical Association, 94*(26), 2058-2062.

Jones, A. (2007). More than 'managing across borders?'The complex role of face-to-face interaction in globalizing law firms. *Journal of economic geography*.

Jung, W., & Lee, J. (2000). *Automotive seat guide line study by comparing anthropometric data between eastern and western people.* Paper presented at the Seoul 2000 FISITA World Automotive Congress.

K Kamp, I., Kilincsoy, Ü., & Vink, P. (2011). Chosen postures during specific sitting activities. *Ergonomics, 54*(11), 1029-1042.

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. *Invest Ophthalmol Vis Sci, 56*(6), 3869-3874. doi:10.1167/iovs.14-16079

Karacan, I., Thornby, J., Anch, A., Williams, R., & Perkins, H. (1978). Effects of high ambient temperature on sleep in young men. *Aviation, space, and environmental medicine, 49*(7), 855-860.

Kawabata, A., & Tokura, H. (1996). Effects of two kinds of pillow on thermoregulatory responses during night sleep. *Applied Human Science, 15*(4), 155-159.

Keane, M., & O'Toole, M. T. (2005). *Miller-Keane encyclopedia and dictionary of medicine, nursing, and allied health (7th edition)*: Saunders.

Kidde. (2016). Kidde History. Retrieved from http://www.kidde.com/home-safety/en/us/about/history/

Kiesler, S., & Cummings, J. N. (2002). What do we know about proximity and distance in work groups? A legacy of research. *Distributed work, 1*, 57-80.

Kilincsoy, Ü., Wagner, A., Bengler, C., Bubb, H., & Vink, P. (2014). *Comfortable rear seat postures preferred by car passengers.* Paper presented at the 5 th International Conference on Applied Human Factors and Ergonomics.

Kim, K. N., Jeoung, J. W., Park, K. H., Kim, D. M., & Ritch, R. (2014). Relationship between preferred sleeping position and asymmetric visual field loss in open-angle glaucoma patients. *American journal of ophthalmology, 157*(3), 739-745.

Kingma, B. R., Frijns, A. J., Schellen, L., & van Marken Lichtenbelt, W. D. (2014). Beyond the classic thermoneutral zone: including thermal comfort. *Temperature, 1*(2), 142-149.

KLM Royal Dutch Airlines. (1956). 'It's a treat to go Dutch' (pp. magazine add). U.S.A.: New Yorker Magazine.

Knijnenburg, R. (2005). *Future passengers side truck seat for DAF*. Confidential graduation report. Industrial Design Engineering. Delft University of Technology. Delft, The Netherlands.

Kollau, R. (2012). Beyond full-flat beds and slim-line seats » How airlines can differentiate the passenger experience 'up in the air.

Konijn, I., Jongejan, B., Berger, M., & Vink, P. (2008). Comfort en bewegen bij staand en half zittend beeldschermwerk. *Tijdschrift voor ergonomie, 33*(2), 14-19.

Kräuchi, K., Cajochen, C., & Wirz-Justice, A. (1997). A relationship between heat loss and sleepiness: effects of postural change and melatonin administration. *Journal of Applied Physiology, 83*(1), 134-139.

Kripke, D. F., Simons, R. N., Garfinkel, L., & Hammond, E. C. (1979). Short and long sleep and sleeping pills. Is increased mortality associated? *Archives of general psychiatry, 36*, 103-116.

Kroemer, K. H. E., & Hill, S. G. (1986). Preferred line of sight angle. *Ergonomics, 29*(9), 1129-1134.

Krupnick, M. (2015). Steep Fees and First-Class Prices, but Private Jets Are Available to More. *New York Times.* Retrieved from nytimes.com/2015/02/17/business/despite-steep-fees-and-first-class-prices-private-jets-are-available-to-more.html

Kryger, M. H., Roth, T., & Dement, W. C. (2016). *Principles and Practice of Sleep Medicine* (6th ed.). Philadelphia, USA: Elsevier - Health Sciences Division.

Kühne, M. (2015). *Thesis: Design of an adjustable headrest enabling sideward leaning and seclusion on long-haul economy flights.* (Master thesis), Delft University of Technology, Delft, The Netherlands. Retrieved from http://repository.tudelft.nl/islandora/object/uuid:84f0ee85-3ec5-45c8-8c36-caed82f2464e

Kuijer, L., & De Jong, A. (2012). Identifying design opportunities for reduced household resource consumption: exploring practices of thermal comfort. *Journal of Design Research 14, 10*(1-2), 67-85.

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.

L Lam, M., Stewart, J., Vogel, A., van Gils, S., de Vries, A., & Weiss, A. (2014). *Improving the premium economy class seat to provide a better experience.* (Confidential AED report for Zodiac Aerospace), Delft University of Technology, Delft.

Lan, L., Pan, L., Lian, Z., Huang, H., & Lin, Y. (2014). Experimental study on thermal comfort of sleeping people at different air temperatures. *Building and Environment, 73*, 24-31.

Langford, G., Meddis, R., & Pearson, A. (1972). Spontaneous arousals from sleep in human subjects. *Psychonomic Science, 28*(4), 228-230.

Law, T. (2013). *The Future of Thermal Comfort in an Energy-Constrained World*: Springer Science & Business Media.

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

Lee, D.-S. (2012). Preferred viewing distance of liquid crystal high-definition television. *Applied ergonomics, 43*(1), 151-156.

Lee-Chiong, T. (2010). *Best of Sleep Medicine*.

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.

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.

Lips, D. M. (2017). *Thesis: design of a lightweight and comfortable aircraft seat*. Retrieved from resolver.tudelft.nl/uuid:eec699e8-9a1a-4069-86d1-3b8996ffb1e1

Liu, S.-F., Lee, Y.-L., & Liang, J.-C. (2011). Shape design of an optimal comfortable pillow based on the analytic hierarchy process method. *Journal of chiropractic medicine, 10*(4), 229-239.

Los Angeles Times. (2016). Karl Forman Weber. *Los Angeles Times*. Retrieved from http://www.legacy.com/obituaries/latimes/obituary.aspx?pid=177934472

Lu, J.-L., & Peeta, S. (2009). Analysis of the factors that influence the relationship between business air travel and videoconferencing. *Transportation Research Part A: Policy and Practice, 43*(8), 709-721.

Lueder, R. (2004). Ergonomics of seated movement a review of the scientific literature. *Ergonomics review of Humanics Ergosystems, Inc*.

Luo, M., Cao, B., Ji, W., Ouyang, Q., Lin, B., & Zhu, Y. (2016). The underlying linkage between personal control and thermal comfort: Psychological or physical effects? *Energy and Buildings, 111*, 56-63.

M Macpherson, R. (1973). Thermal stress and thermal comfort. *Ergonomics, 16*(5), 611-622.

Mannekens, P. (1996). Rug en bed: slaapsystemen en de preventie van rugklachten. *Utrecht/Antwerpen: De Tijdstroom/Polygon*.

Marotte, H., & Timbal, J. (1981). Circadian rhythm of temperature in man: Comparative study with two experiment protocols. *Chronobiologia*.

McCabe, S. J., & Xue, Y. (2010). Evaluation of sleep position as a potential cause of carpal tunnel syndrome: preferred sleep position on the side is associated with age and gender. *Hand, 5*(4), 361-363.

McVey, G. F. (1970). Television: Some viewer-display considerations. *Educational Technology Research and Development, 18*(3), 277-290.

MedicineNet. (2017). Medical Definition of Anatomic orientation terms. Retrieved from medicinenet.com/script/main/art.asp?articlekey=9210

Molenbroek, J. F. (2004). DINED, Anthropometric database. Retrieved from dined.io.tudelft.nl

Molenbroek, J. F. M. (2004). DINED, Anthropometric database. from Delft University of Technology dined.io.tudelft.nl

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.

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.

Montgomery, J., Hislop, H., Connelly, B., & Daniels, L. (2007). Daniel's and Worthingham's muscle testing: techniques of manual examination. *Saunders*.

Mouawad, J. (2013). The Race to Build a Better Business Class. Retrieved from The New York Times website: http://www.nytimes.com/2013/08/04/business/the-race-to-build-a-better-business-class.html?ref=jadmouawad&_r=1

Muzet, A., Libert, J.-P., & Candas, V. (1984). Ambient temperature and human sleep. *Experientia, 40*(5), 425-429.

Muzet, A., Naitoh, P., Townsend, R., & Johnson, L. (1972). Body movements during sleep as a predictor of stage change. *Psychonomic Science, 29*(1), 7-10.

N Nachemson, A., & Elfstrom, G. (1970). Intravital dynamic pressure measurements in lumbar discs. *Scand J Rehabil Med, 2*(suppl 1), 1-40.

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.

Nardi, B. A., & Whittaker, S. (2002). The place of face-to-face communication in distributed work. *Distributed work*, 83-110.

Narita, N., Kanazawa, M., & Okano, F. (2001). Optimum screen size and viewing distance ultra high definition and wide-screen images. *The Journal of Institute of Image Information and Television Engineers, 55*(5), 773-780.

Neistat, C. (2016a). THE $21,000 FIRST CLASS AIRPLANE SEAT. Retrieved from youtube.com/watch?v=84WIaK3bl_s

Neistat, C. (2016b). INCREDIBLE First Class BAR AND SHOWER!!! Retrieved from youtube.com/watch?v=T4L-7S0-mc0

Nicholson, A., & Stone, B. M. (1987). Influence of back angle on the quality of sleep in seats. *Ergonomics, 30*(7), 1033-1041.

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.

Niţă, M. F., & Scholz, D. (2011). Business opportunities in aircraft cabin conversion and refurbishing. *Journal of Aerospace Operations, 1*(1-2), 129-153.

Nohria, N., & Eccles, R. G. (1992). Face-to-face: Making network organizations work.

O Ogier, F. (2015). The Origin of Economy Class. Retrieved from blog.klm.com/the-origin-of-economy-class/

Okamoto, K., Mizuno, K., & Okudaira, N. (1997). The effects of a newly designed air mattress upon sleep and bed climate. *Applied Human Science, 16*(4), 161-166.

Okamoto-Mizuno, K., & Mizuno, K. (2012). Effects of thermal environment on sleep and circadian rhythm. *Journal of physiological anthropology, 31*(1), 14.

Onen, S., Onen, F., Bailly, D., & Parquet, P. (1994). Prevention and treatment of sleep disorders through regulation of sleeping habits. *Presse medicale (Paris, France: 1983), 23*(10), 485-489.

P Palca, J., Walker, J., & Berger, R. (1986). Thermoregulation, metabolism, and stages of sleep in cold-exposed men. *Journal of Applied Physiology, 61*(3), 940-947.

Pang, L., Qin, Y., Liu, D., & Liu, M. (2014). Thermal comfort assessment in civil aircraft cabins. *Chinese Journal of Aeronautics, 27*(2), 210-216.

Park, S.-J., Kim, J.-S., Min, B.-C., Kwon, K.-S., & Jeong, B.-Y. (2000). *Preferred Pressure Distribution and Shift Ratings of Comfort on Auto Bed.* Paper presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting.

Pasut, W., Zhang, H., Arens, E., Kaam, S., & Zhai, Y. (2013). Effect of a heated and cooled office chair on thermal comfort. *HVAC&R Research, 19*(5), 574-583.

Paulsen, F., & Waschke, J. (2011). *Sobotta Atlas of Human Anatomy - Head, Neck and Neuroanatomy* (Vol. 3): Urban & Fischer.

Pennig, S., Quehl, J., & Rolny, V. (2012). Effects of aircraft cabin noise on passenger comfort. *Ergonomics, 55*(10), 1252-1265.

Persson, L. (2006). Neck pain and pillows–A blinded study of the effect of pillows on non-specific neck pain, headache and sleep. *Advances in Physiotherapy, 8*(3), 122-127.

Persson, L., & Moritz, U. (1998). Neck support pillows: a comparative study. *Journal of manipulative and physiological therapeutics, 21*(4), 237-240.

Peterson, B. (2012). Meet the New Business Class. Retrieved from http://www.cntraveler.com/stories/2012-09-19/lufthansa-airline-new-business-class

Pheasant, S., & Haslegrave, C. M. (2005). *Bodyspace: Anthropometry, ergonomics and the design of work (3rd edition)*: CRC Press.

Pierrette, M., Parizet, E., Chevret, P., & Chatillon, J. (2015). Noise effect on comfort in open-space offices: development of an assessment questionnaire. *Ergonomics, 58*(1), 96-106.

Polga, D. J., Beaubien, B. P., Kallemeier, P. M., Schellhas, K. P., Lew, W. D., Buttermann, G. R., & Wood, K. B. (2004). Measurement of in vivo intradiscal pressure in healthy thoracic intervertebral discs. *Spine, 29*(12), 1320-1324.

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.

Q

Quaranta Leoni, F. M., Molle, F., Scavino, G., & Dickmann, A. (1994). Identification of the preferential gaze position through evaluation of visual fatigue in a selected group of VDU operators. *Documenta ophthalmologica, 87*(2), 189-197.

Quigley, C., Southall, D., Freer, M., Moody, A., & Porter, J. M. (2001). *Anthropometric study to update minimum aircraft seating standards*. Retrieved from dspace.lboro.ac.uk/2134/701

R

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.

Raymann, R. J., Swaab, D. F., & Van Someren, E. J. (2005). Cutaneous warming promotes sleep onset. *Am J Physiol Regul Integr Comp Physiol, 288*(6), R1589-1597. doi:10.1152/ajpregu.00492.2004

Reed, D. (2006). Technology Trends in IFE - Part one. *Avion, 1,* 8-16.

Reed, D. L., & Sacco, W. P. (2016). Measuring sleep efficiency: what should the denominator be? *Journal of clinical sleep medicine: JCSM: official publication of the American Academy of Sleep Medicine, 12*(2), 263.

Remington, L. A. (2012). Clinical anatomy and physiology of the visual system 3rd edition: Missouri.

Rithalia, S. (2005). Assessment of patient support surfaces: principle, practice and limitations. *Journal of Medical Engineering & Technology, 29*(4), 163-169.

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.

Rosenbaum-Elliott, R., Percy, L., & Pervan, S. (2015). *Strategic brand management*: Oxford University Press, USA.

Rotte, T. A., Otten, M., Hayde, Z. M., Aus dem Kamen, V., Mösinger, P., & Sanchez, J. E. (2014). *Pressure distribution and discomfort: determining design drivers for the design of a headrest side support*. Unpublished manuscript, Industrial Design Engineering, Delft University of Technology.

Roy, J., & Filiatrault, P. (1998). The impact of new business practices and information technologies on business air travel demand. *Journal of Air Transport Management, 4*(2), 77-86.

S Sacco, I. C., Pereira, I. L., Dinato, R. C., Silva, V. C., Friso, B., & Viterbo, S. F. (2015). The effect of pillow height on muscle activity of the neck and mid-upper back and patient perception of comfort. *Journal of manipulative and physiological therapeutics, 38*(6), 375-381.

Sakamoto, K., Aoyama, S., Asahara, S., Yamashita, K., & Okada, A. (2008). *Relationship between viewing distance and visual fatigue in relation to feeling of involvement.* Paper presented at the Asia-Pacific Conference on Computer Human Interaction.

Salzarulo, P., Fagioli, I., Lombardo, P., Gori, S., Gneri, C., Chiaramonti, R., & Murri, L. (1999). Sleep stages preceding spontaneous awakenings in the elderly. *Sleep Res Online, 2*(3), 73-77.

Sato, K., Kikuchi, S., & Yonezawa, T. (1999). In vivo intradiscal pressure measurement in healthy individuals and in patients with ongoing back problems. *Spine, 24*(23), 2468.

Schifferstein, H. N., & Hekkert, P. (2011). *Product experience*: Elsevier.

Schmidt, F. P., Basner, M., Kröger, G., Weck, S., Schnorbus, B., Muttray, A., . . . Warnholtz, A. (2013). Effect of nighttime aircraft noise exposure on endothelial function and stress hormone release in healthy adults. *European heart journal, 34*(45), 3508-3514.

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.

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.

Schultheis, U. (2015, September 28th).

Schultheis, U. (2016a, March 23rd).

Schultheis, U. (2016b). Airline Passenger Comfort and Safety. Retrieved from www.linkedin.com/pulse/airline-passenger-comfort-safety-dr-udo-schultheis

Seat Guru. (2016). British Airways Seat Maps - Boeing 747-400 (744) V3. Retrieved from seatguru.com/airlines/British_Airways/British_Airways_Boeing_747-400_D.php

Sewitch, D. E., Kittrell, E. M. W., Kupfer, D. J., & Reynolds, C. F. (1986). Body temperature and sleep architecture in response to a mild cold stress in women. *Physiology & behavior, 36*(5), 951-957.

Shafiquzzaman Khan, M. (2003). Effects of masking sound on train passenger aboard activities and on other interior annoying noises. *Acta Acustica united with Acustica, 89*(4), 711-717.

Shankland, S. (2014). Want major new aircraft designs? Wait until 2030(15 Oktober 2015). Retrieved from Cnet website: http://www.cnet.com/news/want-major-new-aircraft-designs-wait-until-2030/

Shields, N., Capper, J., Polak, T., & Taylor, N. (2006). Are cervical pillows effective in reducing neck pain? *New Zealand Journal of Physiotherapy, 34*(1), 3-9.

Sillers, P. (2016). To Disturb, or Not to Disturb a Sleeping Passenger? Airlines Get the Message. Retrieved from http://apex.aero/2016/10/31/disturb-sleeping-passenger-airlines-message

Simons, M., & Spencer, M. (2007). *Extension of flying duty period by in-flight relief*. (TNO-DV 2007 C362). Soesterberg: TNO Retrieved from publications.tno.nl/publication/606495/U7QF7J/SB-2007-C362.pdf.

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., Grondelle, E. D., Schultheis, U., & Vink, P. (invited and submitted). Neck posture and muscle activity in a reclined business class aircraft seat watching IFE with and without head support. *Applied ergonomics*.

Snider, S. R. (2016, June).

Snijders, C. J., Nordin, M., & Frankel, V. H. (1995). *Biomechanica van het spier-skeletstelsel; grondslagen en toepassingen. Lemma, Utrecht*. Retrieved from

Spafax Consulting. (1998). *Passenger Inflight Entertainment Research (PIER 98)*. Spafax Consulting in association with Travel Research Centre (as cited in Alamdari 1999).

Spooner, S. (1925, 16 April). An Aerial "Picture Theatre". *Flight, 225*.

Standring, S. (2015). *Gray's Anatomy: The Anatomical Basis of Clinical Practice* (Vol. 41). London, UK: Elsevier Health Sciences.

Storper, M., & Venables, A. J. (2004). Buzz: face-to-face contact and the urban economy. *Journal of economic geography, 4*(4), 351-370.

Straker, L., Pollock, C., Burgess-Limerick, R., Skoss, R., & Coleman, J. (2008). The impact of computer display height and desk design on muscle activity during information technology work by young adults. *Journal of electromyography and Kinesiology, 18*(4), 606-617.

Sumers, B. (2017). Why International First Class Is Slowly Disappearing From Airlines. *Skift*. Retrieved from skift.com/2017/03/13/why-international-first-class-is-slowly-disappearing-from-airlines/

Szeto, G. P., Straker, L., & Raine, S. (2002). A field comparison of neck and shoulder postures in symptomatic and asymptomatic office workers. *Applied ergonomics, 33*(1), 75-84.

T Taylor, J. H., Parker Jr, J. F., & West, V. R. (1973). *Bioastronautics Data Book, 2nd Edition NASA publication SP-3006*. Washington DC: NASA.

Tikuisis, P., & Ducharme, M. B. (1996). The effect of postural changes on body temperatures and heat balance. *European journal of applied physiology and occupational physiology, 72*(5-6), 451-459.

Tilley, A. (1993). The measure of man and woman: human factors in design.

Torenbeek, E. (1996). *Synthesis of subsonic airplane design: an introduction to the preliminary design of subsonic general aviation and transport aircraft, with emphasis on layout, aerodynamic design, propulsion and performance*: Springer Science & Business Media.

Travell, J. (1967). Mechanical headache. *Headache: The Journal of Head and Face Pain, 7*(1), 23-29.

Travell, J. G., & Simons, D. G. (1992). *Myofascial pain and dysfunction: the trigger point manual* (Vol. 2): Lippincott Williams & Wilkins.

TripAdvisor LLC. (2018). Aircraft seat maps, flight shopping and flight information. Retrieved from seatguru.com

U U.S. Department of Transportation Federal Aviation Administration. (2012). *Flightcrew Member Duty and Rest Requirements (Final Rule on replacement of 14 CFR Part 12)*. (FAA-2009-1093). Federal Register Retrieved from faa.gov/regulations_policies/rulemaking/recently_published/media/2120-AJ58-FinalRule.pdf.

U.S. Department of Transportation Federal Aviation Administration. (2013). *Flight crew member rest facilities*. (AC No. 117-1). Retrieved from faa.gov/documentLibrary/media/Advisory_Circular/AC_117-1.pdf.

V Van der Heijden, I. (2016). *A non-pharmacological and scientifically proven solution for people suffering from insomnia.* (Master of Science Master thesis), Delft University of Technology, Delft. Retrieved from repository.tudelft.nl/islandora/object/uuid%3A85ef7332-1713-4973-bece-3ea0f7203dc6?collection=education (uuid:85ef7332-1713-4973-bece-3ea0f7203dc6)

Van der Klooster, K. (2015). *Thesis: New headrest concept with integrated IFE solution enhancing passengers' privacy - and in-flight experience*. Retrieved from resolver.tudelft.nl/uuid:d8f17050-f9ec-4258-9b65-7b0e80a70af0

Van Deun, D., Verhaert, V., Willemen, T., Haex, B., & Vander Sloten, J. (2012). Uw bed beinvloedt uw slaap.

Van Dieen, J., De Looze, M., & Hermans, V. (2001). Effects of dynamic office chairs on trunk kinematics, trunk extensor EMG and spinal shrinkage. *Ergonomics, 44*(7), 739-750.

van Meurs, O. (2017). *Designing a crew seat with a sleep opportunity: Optimizing crew rest by designing a seat that facilitates comfort but does not take up more space.* (Master thesis), Delft University of Technology, Delft. Retrieved from repository.tudelft.nl/islandora/object/uuid%3Ab1bbacc3-74a1-4460-a007-fd93adf76cec

van Rosmalen, D. M. K., Groenesteijn, L., Boess, S. U., & 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.

van Rosmalen, D. M. K., Groenesteijn, L., Boess, S. U., & Vink, P. (2010). Eisen aan een loungestoel om naar een scherm te kijken. *Tijdschrift voor ergonomie, 2, 35, 4-10*.

van Veen, S., & Vink, P. (2016). Can Prior Experience Influence Seating Comfort Ratings? *ergonomics in design, 24*(2), 16-20.

van Veen, S. A., 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

Verhaert, V. (2011). *Ergonomic analysis of integrated bed measurements- towards smart sleep systems.*

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.

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. (2014a) *People want to press the button themselves; interview/Interviewer: J. Wassink*. (Vol 3), Delft Outlook, Delft.

Vink, P. (2014b, 4 june 2014). *The sweetness of discomfort: design the journey.* Paper presented at the Inaugural address.

Vink, P. (2014c). *The sweetness of discomfort: Designing the journey*. Inaugural address. (uuid:517db1ea-9e10-4ba7-9bae-f012698eddb3). Delft University of Technology, Delft.

Vink, P. (2015, September 28).

Vink, P. (2016). *Vehicle seat comfort and design*: TU Delft Library.

Vink, P., & Brauer, K. (2011). Aircraft interior comfort and design (ergonomics design management: theory and applications): CRC Press, Boca Raton.

Vink, P., & Hallbeck, S. (2012). Editorial: Comfort and discomfort studies demonstrate the need for a new model. *Applied ergonomics, 43*(2), 271-276.

Vink, P., & Lips, D. (2017). Sensitivity of the human back and buttocks: The missing link in comfort seat design. *Applied ergonomics, 58*, 287-292.

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 Annual Meeting.

Vink, P., Vledder, G., Smulders, M., Bronkhorst, R. E., & Hiemstra-van Mastrigt, S. (2017). *KLM World Business Class seat study (confidential)*. Delft University of Technology/IPSOS.

Vledder, G. (2017). *Redesign of a business class armrest: Improvement of arm comfort for watching in flight entertainment and reading.* (Master thesis), Delft University of Technology, Delft. Retrieved from repository.tudelft.nl/islandora/object/uuid%3Ae6301838-28da-457e-8b52-810ecc4b2ee1?collection=education (uuid:e6301838-28da-457e-8b52-810ecc4b2ee1)

Vokac, Z., & Hjeltnes, N. (1981). Core-peripheral heat redistribution during sleep and its effect on rectal temperature. *Night and Shift Work: Biological and Social Aspects. Pergamon Press, Oxford*, 109-115.

Von Noorden, G., & Campos, E. (2002). Physiology of the ocular movements. *Binocular Vision and Ocular Motility: Theory and Management of Strabismus, 6th edition. St Louis: Mosby*, 52-84.

W

Waterhouse, J., Fukuda, Y., & Morita, T. (2012). Daily rhythms of the sleep-wake cycle. *J Physiol Anthropol, 31*, 5. doi:10.1186/1880-6805-31-5

Webber Aircraft LLC. (2010). Company Profile. Retrieved from http://web.archive.org/web/20101201105714/http://weberair.com/

Weber Aircraft LLC. (2000a). Ejection Seats. Retrieved from https://web.archive.org/web/19981207032420/http://www.weberair.com/

Weber Aircraft LLC. (2000b). Enter Aircraft. Retrieved from https://web.archive.org/web/19981207032420/http://www.weberair.com/

Weber Aircraft LLC. (2000c). Weber Aircraft today. Retrieved from https://web.archive.org/web/19981207032420/http://www.weberair.com/

Weber Aircraft LP. (2002). Company Profile. Retrieved from http://web.archive.org/web/20021010101017/http://www.weberair.com/marketing.htm

Weber Showcase and Fixture Company Inc. (1942). 'Weber Aircraft Division Produces

For War'. *Aviation, 42*(6), 182. Retrieved from http://www.gettyimages.co.uk/detail/news-photo/world-war-ii-era-black-and-white-advertisement-weber-news-photo/181388276#world-war-iiera-black-and-white-advertisement-weber-aircraft-division-picture-id181388276

Wendover Productions (Producer). (2017, 16-03-2017). The Economics of Airline Class. Retrieved from youtu.be/BzB5xtGGsTc

Weston, H. C. (1953). Visual fatigue with special reference to lighting. *Lighting Research and Technology, 18*(2 IEStrans), 39-66.

Weterings, A., & Boschma, R. (2009). Does spatial proximity to customers matter for innovative performance?: Evidence from the Dutch software sector. *Research Policy, 38*(5), 746-755.

White, J. N. (2012). A History of Inflight Entertainment. Retrieved from

Wiki Commons. (2016a). Antimacassar. Retrieved from en.wikipedia.org/wiki/Antimacassar

Wiki Commons. (2016b). Zodiac Aerospace. Retrieved from en.wikipedia.org/wiki/Zodiac_Aerospace

Wilde-Frenz, J., & Schulz, H. (1983). Rate and distribution of body movements during sleep in humans. *Perceptual and motor skills, 56*(1), 275-283.

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.

Willemen, T., Van Deun, D., Verhaert, V., Pirrera, S., Exadaktylos, V., Verbraecken, J., . . . Sloten, J. V. (2012). Automatic sleep stage classification based on easy to register signals as a validation tool for ergonomic steering in smart bedding systems. *Work, 41*(Supplement 1), 1985-1989.

Willemen, T., Van Deun, D., Verhaert, V., Vandekerckhove, M., Exadaktylos, V., Verbraecken, J., . . . Vander Sloten, J. (2014). An evaluation of cardiorespiratory and movement features with respect to sleep-stage classification. *IEEE journal of biomedical and health informatics, 18*(2), 661-669.

Williams, A. M., & Irurita, V. F. (2005). Enhancing the therapeutic potential of hospital environments by increasing the personal control and emotional comfort of hospitalized patients. *Applied Nursing Research, 18*(1), 22-28.

World Health Organization. (2009). *Guide to hygiene and sanitation in aviation*: World Health Organization.

Wright, K. P., McHill, A. W., Birks, B. R., Griffin, B. R., Rusterholz, T., & Chinoy, E. D. (2013). Entrainment of the human circadian clock to the natural light-dark cycle. *Current Biology, 23*(16), 1554-1558.

Y

Yeh, Y.-Y., & Lee, D.-S. (2012). *Characteristics of subtitle on preferred viewing distance and subjective preference of liquid crystal display high-definition television.* Paper presented at the Image and Signal Processing (CISP), 2012 5th International Congress on.

Yim, J. E. (2015). Optimal Pillow Conditions for High-Quality Sleep: A Theoretical Review. *Indian Journal of Science and Technology, 8*, 135.

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

Yoshida, H., Kamijo, M., & Shimizu, Y. (2012). A Study to Investigate the Sleeping Comfort of Mattress using Finite Element Method. *Kansei Engineering International Journal, 11*, 155-162.

Yun, M. H., Donges, L., & Freivalds, A. (1992). Using force sensitive resistors to evaluate the driver seating comfort. *Advances in Industrial Ergonomics and Safety IV (London: Taylor and Francis)*, 403-410.

Z Zee, P. C., & Goldstein, C. A. (2010). Treatment of shift work disorder and jet lag. *Current treatment options in neurology, 12*(5), 396-411.

Zenk, R. (2008). *Objektivierung des Sitzkomforts und seine automatische Anpassung.* Universität München.

Zenk, R., Franz, M., Bubb, H., & Vink, P. (2012). Technical note: spine loading in automotive seating. *Applied ergonomics, 43*(2), 290-295.

Zodiac Aerospace. (2012). Our Heritage. Retrieved from www.zodiacaerospace.com/en/corporate/history/our-heritage

Zodiac Aerospace. (2016a). *2015/2016 Q2 Sales Revenue: a year of transformation*. Retrieved from zodiacaerospace.com/sites/default/files/content-files/actualites/160315-zc-cp-en-h1_sales_2015-2016_-_final_1.pdf

Zodiac Aerospace. (2016b). *Travel Journal: Annual report 2014-2015*. Retrieved from zodiacaerospace.com/sites/default/files/content-files/push-publication/en_zodiac_aerospace_ra2014-2015_travel_journal_bd.pdf

Zodiac Aerospace. (2016c). Zodiac Seats US. Retrieved from https://web.archive.org/web/20160503181908/http://www.zodiacaerospace.com/en/zodiac-seats-us

Zodiac Aerospace. (n.d.). Zodiac Seats France. Retrieved from zodiacaerospace.com/en/zodiac-seats-france

11 Acknowledgements

Hereby I would like to thank the following people for their support and/or contribution to this project:

I want to acknowledge the contribution of dr. Udo Schultheis for backing my research and (original) graduation project, inviting me to join the Human Factors and Ergonomics team at Zodiac Seats US and mentoring me during the beginning of my stay. Thank you for believing in me and in my project, and for your counselling in scientific writing. It's a shame that the duration of our cooperation was limited.

Big thanks to the Human Factors and Ergonomics team and allied colleagues at R&D and Legal at Zodiac Seats US for all their your, advice, the many jokes and loughs and keeping an eye on me; Samuel 'Rusty' Snider, Jeffery Sikorsk, Foek Le, Joyce Bouwens, Raul Reyes, Marc Kinard, Michael Murray, Joshua Choe, Reza Mansouri and many others. Thanks to the Human Factors and Ergonomics lab at ZSUS for letting me borrow the Delsys® EMG equipment to finish my EMG study in the Netherlands. Thanks to ZGEU R&T and IT department for your support before and after my time at ZSUS, with a special thanks to Peter Ruig, ir. Jenny Tsay, ing. Paul Vlaming, ing. Jochem Wartena, ing. Tom Scheuder, Rutger Landsaat and Sabine Agterberg for your help and support.

My co-graduate interns, room- and running mates in Texas; Stefan Akkerman and Daan Lips. Thanks guys for all the fun and exercise in our leisure time and all the sparring at the office. I enjoyed our time together and really appreciated your support.

Great thanks to prof.dr. Alessandro Naddeo M.D. and prof. Nicola Cappetti of the University of Salerno for sharing your thoughts on sleeping comfort and biomechanics and conducting multiple AnyBody simulations. I really enjoyed our conversations. Thanks to prof.dr.ir. Richard Goossens for the discussions and sharing your knowledge on biomechanics, prof.dr. Bart Haex of the Maastricht University for sharing your knowledge on sleeping postures and Ir. Hanneke Thieme for all your support and guidance over the years.

Thanks to Indy van der Heijden for sharing your insights and perspective on sleep. Jochen Lohrmann for taking the time to share your perspective on aircraft seating and headrest design. Joyce Bouwens for being my sparring partner, supporting me, the many laughs, all your advice and pressuring me every now and then when needed. Maximilian Wegner for the laughs, discussions and sharing your knowledge and thought on (automotive) seating. Bram van der Grinten for helping ideating on dynamic mechanism design and supporting me.

Special thanks to Samuel 'Rusty' Snider and Bertus Naagen for your great help with all my experiments with such enthusiasm. I really appreciate the time you guys always made free for me to help out, volunteered to get experimented on, the many fun talks and your humour.

A big thanks to many interviewees and study participants, including from KLM and KCS. You all were very friendly, helpful, enthusiastic and open. I really enjoyed our many conversations and learned an awful lot from you all. Without your help, my studies would not be possible.

Thanks to the scientific committee – Prof. Alessandro Naddeo, Prof. Peter Vink, Prof. Neil Mansfield, Dr. Susanne Frohriep, Prof. Nicola Cappetti, Prof. Richard Goossens, Dr. Jamie Mackrill and Dr. Diane Gyi – of the 1st International Comfort Conference for inviting me to present and selecting my paper for publication in Applied Ergonomics.

My friends and family for supporting me. A special thanks to my parents and brother, for always supporting and believing in me; I could not have done it without you. My dear friends Mercedes Leipoldt, Simone de Jong, Gina Henselmans, Wendy v.d.Horst and Karlien Kleissen for always being there for me, helping as a sparring partner, pushing me when needed and supporting me through and through. Alexander Weiss, Anette de Vries, Karin Boer, Thekla van Lingen, Zoé Martial, Elske van der Ende, Jenny Tsay and Ameya Waingankar for supporting me through this project. A big thanks to Gina Henselmans, Wendy v.d.Horst, Simone de Jong, Jeroen Faro, Karlien Kleissen and Leroy Huikeshoven for proofreading.

And last but not least a big thanks to my coach Elmer van Grondelle MBA and chair prof.dr. Peter Vink for supporting me, mentoring me, sharing their knowledge and experience and their incredible patience with me. Thank you Elmer for your criticism, keeping me focussed and guiding me through the complexity of company politics and project management and above all; always supporting me and believing in me. Thank you Peter Vink for your endless enthusiasm and support, believing in me and my project and the many hours of discussions, helping me to publish, excel academically and inviting me to the IQPC Automotive Seating Conference 2016 in Hamburg, Germany and the International Comfort Conference in Salerno, Italy. It was an absolute joy and privilege to work with you both.

Chapter 12 **Page**

12

12 Glossary

In the world of aviation, biomechanics and medicine a lot of acronyms and jargon is used, as well in this thesis. Since not all readers will be familiar with these terms, this glossary will offer an overview on abbreviations and jargon, followed by an overview of anatomical terminology, describing positions and orientation of limbs, orientation of view, positions of muscles and bones.

12.1 Abbreviations and jargon

A	Abduction (body)	The motion of a limbs or other body parts that pulls away from the midline of the body.
	Abduction (eye)	Outwards rotation of the eyes (looking outward). See §12.3.2 for a visual representation.
	AC	Aircraft
	Accommodation (eye)	The automatic adjustment of the focus of the eye by flattening or thickening of the eye's lens.
	Acromion	The bony process on the scapula (shoulder blade). See §12.3.3 for a visual representation.
	Adduction (body)	The movement of a body part toward the body's midline.
	Adduction (eye)	Inwards rotation of the eyes (looking inward towards each other). See §12.3.2 for a visual representation.
	Aft-facing	Facing towards the tail (back) of the aircraft.
	Angled-flat seat	When in fully reclined position, the seat surface is flat (180˚) but under a slight angle, making the passenger not lay completely horizontal. Passengers often find these seats to be very comfortable for relaxing and working, but not conducive to sleep when in the fully reclined position due to the awkward angle and the tension to slide down out of the seat.
	Anterior	Anatomical description for the front, as opposed to the posterior. See for visual representation §12.2.
	Antimacassar	Also known as a headrest cover. A small cloth placed on the backrest or headrest of an aircraft seat to prevent soiling of the permanent fabric for durability and hygiene purposes (Wiki Commons, 2016a). This gets replaced by cleaning staff every day or every turnaround, depending on the airline's wishes (World Health Organization, 2009).
	Apex	The top or highest part of something, here mainly meant as the highest point of a cushion.
	Atlas (C1)	Most superior (first) cervical vertebra of the spine and with the axis forms the joint connecting the skull and spine. The atlas and axis are specialized to allow a greater range of motion than normal vertebrae. They are responsible for the nodding and rotation movements of the head. See §12.3.4 for a visual representation.
B	BC / BiC	Business Class
	BCP	Business Class Passenger.
	Bilateral reaching	Simultaneous use of both hands in a reaching activity.
	Bulkhead (seating)	A separation wall in an aircraft. Seats facing a bulkhead have no seats in front and in economy class therefore often feature the traytabel and/or IFE monitor in the armrest or are mounted on the bulkhead. On long-haul flights bulkheads often feature mountings for baby bayonets.
C	CA	Cabin Attendant, also known as Flight Attendant. Please see FA for more information.
	CAD	Computer Aided Design. The creation, modification, analysis, or optimisation of a design with the use of a computer.
	Canthus	Either corner of the eye where the upper and lower eyelids meet. See §12.3.3 for a visual representation.
	Carrier	The airline that carries out the flight. Usually multiple cooperating airlines work together on one plane, of which the owner is considered the carrier (Lips, 2017). Carrier is also commonly used as a synonym of airline.
	CC	Cabin Crew
	Clavicle	Collarbone. See §12.3.4 for a visual representation.

	Corporate	A Zodiac nickname for Zodiac Headquarters in Plaisir, France.
	Coronal	The anatomical term of the location on the human body, seen from the coronal plane (also known as the frontal plane).
	Cradle-style seat	Business class seat with limited recline, offering good space and comfort. These seats can be found in domestic business class in 2-2 and 2-2-2 configurations, although they are installed less these days in favour of angled-flat and full flat seats.
D	Deep sleep	Stage 3 and 4 of sleep. In this phase it is very difficult to wake someone. In deep sleep, there is no eye movement or muscle activity. The sleeper is less responsive to the environment; many environmental stimuli no longer produce any reactions. Slow-wave sleep is thought to be the most restful form of sleep, the phase which most relieves subjective feelings of sleepiness and restores the body (Waterhouse et al., 2012), due to the production of growth hormones (Coenen, 2006).
	Deorsumversion	Also known as infraversion or depression is the downward deviation (looking downward) of both the eye (Keane & O'Toole, 2005; Remington, 2012; Von Noorden & Campos, 2002). See §12.3.2 for a visual representation.
	Distal	Anatomical description for further from the beginning, as opposed to proximal. See for visual representation §12.2.
E	EASA	European Aviation Safety Agency, which is the European aviation authority, is primarily responsible for the advancement, safety and regulation of civil aviation.
	EC	Economy Class
	ECP	Economy Class Passenger
	Egress	Exit a row of seats including standing up.
	EMG	Electromyography. An electrodiagnostic medicine technique for evaluating and recording the electrical activity produced by skeletal muscles.
	sEMG	Surface electromyography. Non-invasive EMG (see EMG) recording muscle activity from the surface above the muscle on the skin.
	Extension	A straightening movement that *increases* the angle between a segment and its proximal segment. E.g. bending the head backwards to the back.
F	FA	Flight Attendant, also known as a Cabin Attendant (CA). The amount of bars describes the rank of a FA, which depends on the airline. For some carriers, the system works as the following: a FA-I works mainly in EC, where FA-II work mainly in BC or FC, but also may be working in EC. An FA-III is a purser-assistants, who mainly supervise EC, but may also be located in BC or FC. A FA-IIII is a purser, who is responsible of the entire cabin and manages the CC on short to medium haul flights. On long haul flights pursers are responsible for EC. A FA-IIIIS is a senior purser and is the highest in rank after the pilots. He/she is responsible for the entire cabin and is mainly located in BC or FC on ICA.
	FAA	Federal Aviation Administration, which is the USA aviation authority, is primarily responsible for the advancement, safety and regulation of civil aviation, as well as overseeing the development of the air traffic control.
	Faux flat	Lie-flat surfaced seat at an angle.
	FC / FiC	First Class
	FCP	First Class Passenger
	FEA	Final Elements Analysis
	Flexion	A bending movement that *decreases* the angle between a segment and its proximal segment. E.g. bending the head forward to the chest.

H	Horizontal	Parallel to the floor or a plane passing through the standing body parallel to the floor. See for visual representation §12.2.
	HQ	Headquarters
I	IATA	International Air Transport Association, the trade association of most of the world's airliners, who account for carrying approximately 83% of total Available Seat Kilometers air traffic (IATA, 2016c).
	ICA	Intercontinental flight, a.k.a. a long haul flight.
	IDE	Faculty Industrial Design Engineering of the Delft University of Technology.
	IFE	In Fligth Entertainment, the screens on board of an aircraft to entertain passengers, featuring (depending on what the airline offers) movies, (live) TV, games, interactive maps, magazines, etc.. These screens are mainly mounted at the upper part of the backrest and for bulkhead seats mounted on an arm, which can be stowed in the armrest.
	Inferior	Anatomical description for below, as opposed to superior. See for visual representation §12.2.
	Inferior oblique	Eye muscle responsible for extorsion, elevation and abduction. See §12.3.2 for a visual representation.
	Inferior rectus	Eye muscle responsible for depression, adduction and support extorion (rotate laterally). See §12.3.2 for a visual representation.
	Ingress	Enter a row of seats including sitting down.
	I/O	Input/output in electronics. It is commonly used to describe port connections for electronic and computer systems.
L	Lateral	Anatomical description for toward the left or right side of the body, as opposed to medial. See for visual representation §12.2.
	Lateral posture	Lying on the side.
	Lateral rectus	Eye muscle responsible for abduction. See §12.3.2 for a visual representation.
	Long haul flight	The classification of flight duration is different among multiple sources. A long haul flight is often classified as a flight, which takes 6-8 or 6-12 hours.
	LOPA	Layout of Passenger Accommodations, aka an Aircraft Interior Configuration Document. This is an engineering diagram of the aircraft's cabin interior that includes, but is not limited to, locations of passenger and flight attendant seats, emergency equipment, exits, lavatories, and galleys. It leads the reviewer through the interior design/layout and is the document that certifies the interior components and installation (IATA, 2016b).
	LPD	Localised Postural Discomfort
M	Medial rectus	Eye muscle responsible for adduction. See §12.3.2 for a visual representation.
	Medium haul flight	The classification of flight duration is different among multiple sources. A medium-haul flight lasts from 3-4 to 6-8 hours or more.
	Moderate Turbulence	Changes is altitude and/or attitude occur but with more intensity than light turbulence. Aircraft remains in control at all times. In the aircraft this will result in the following conditions: liquids are splashing out of cups, difficulties to walk or stand without balancing or holding on to something, carts are difficult to maneuver and passengers feel definite strain against seat belt.
	Monument	A pre-assembled non-structural element of the cabin, such as galleys, cabinets, lavatories, bulkheads and dividers, which are installed in aircraft cabins. These elements are bought from catalogues by airliners; see §4.2 for more information.
N	NASA	National Aeronautics and Space Administration.

	NREM	Non REM, which contains sleep stages 1 and 2 (light sleep) and stages 3 and 4 (deep sleep).
O	OEM	Original equipment manufacturer: a company that produces parts and equipment that may be marketed by another manufacturer, as part or sub-assembly of their own product. E.g. a tube manufacturer is an OEM, providing tubes to a seat manufacturer, which machines them into seat spreaders.
P	PAX	Passenger Seat Place, which stands for one passenger seat or one passenger depending on the context.
	PEC	Premium Economy Class.
	PECP	Premium Economy Class Passenger
	PED	Personal Electronic Device
	Phablet	A portmanteau of the words phone and tablet, describing a class of mobile computing devices designed to combine or straddle the size format of smartphones and tablets, on average ranging between 5-7 inch in screen diameter.
	Prone	Anatomical description for with the front or ventral surface downward (lying face down), as opposed to supine. See for visual representation §12.2.
	Prone posture	Lying on the chest with the face down.
	Purser	See FA.
R	REM	Rapid Eye Movement. REM sleep is a kind of sleep that occurs at intervals during the night and is characterized by rapid eye movements, more dreaming and bodily movement, and faster pulse and breathing.
	RSI	A repetitive strain injury (RSI) is an injury to the musculoskeletal and nervous systems that may be caused by repetitive tasks, forceful exertions, vibrations, mechanical compression, or sustained or awkward positions.
	Retroflexion	The backward movement of a limb from its neutral position.
	Retrofit	The overhauling of an old seat (fabrics and cushions) and the addition of new technologies or features to the older seating system.
S	Sagittal	Anatomical description for a vertical plane passing through the standing body from front to back. The mid-sagittal, or median plane, splits the body into left and right halves. See for visual representation §12.2.
	Scapulae	Shoulder blades. See §12.3.4 for a visual representation.
	SE	Sleep efficiency: a value to express the effectiveness of a full sleep cycle, as used in insomnia research and practice, often expressed as a percentage of total sleep time (TST) to time in bed (TIB) (=TST/TIB•100). It is however debatable if this is the right way to express SE, as TIB includes also non-sleep related activities in bed (e.g. reading) and excludes time out of bed (e.g. due to sleep discontinuity) (D. L. Reed & Sacco, 2016).
	Short haul flight	The classification of flight duration is different among multiple sources. A long short haul flight is a flight, which takes less than 3-4 hours.
	Superior	Anatomical description for above, as opposed to inferior. See for visual representation §12.2.
	Superior rectus	Eye muscle responsible for elevation, adduction and intorsion (rotate medially). See §12.3.2 for a visual representation.
	Superior oblique	Eye muscle responsible for intorsion (medial rotation), abduction and depression. See §12.3.2 for a visual representation.
	Supine posture	Lying on the back with the face up.

	Sursumduction	Elevation of the eyes (looking up). See §12.3.2 for a visual representation.
	SVP	Senior vice president, a senior management position in business.
	SWS	Slow Wave Sleep, a.k.a. deep sleep: the stages 3+4 of nonREM sleep.
T	Temple	The side of the head behind the eyes. See §12.3.3 for a visual representation.
	Temporalis	The side of the head behind the eyes. See §12.3.3 for a visual representation.
	TIB	Time In Bed: the amount of time spend in bed, including sleep.
	Tragus	A small pointed eminence of the outer ear. See §12.3.3 for a visual representation.
	TST	Total Sleep Time: the amount of time sleeping (nonREM and REM).
	TTL	Taxi, Take-off and Landing. This term is generally used as naming the upright seat position, which is the required Taxi, Take-off and Landing position for safety reasons.
	TU Delft	Delft University of Technology
	Turnaround	The process of unloading, loading and servicing an aircraft at an airport.
U	USAF	United States Air Force.
	Ultra long haul	The classification of flight duration is different among multiple sources. An utra long haul flight is often classified as a flight, which takes over 12 hours.
	Usecue	Cues to make a user understand function, guide a user or attracts a user's attention in a product or in a human-product interaction. For further reading one use cues, Schifferstein and Hekkert (2011) *Product experience* is recommended.
V	VDU	Visual Display Unit
	Vergence	Disjunctive movement of the eyes in opposite directions in adjusting to near or far vision (Keane & O'Toole, 2005).
	Vertebra prominens (C7)	The seventh cervical vertebra. See §12.3.4 for a visual representation.
	VOD	Video On Demand. It offers users to control what and when they watch e.g. a movie (Alamdari, 1999).
Z	ZSUS	Zodiac Seats US. For more, see Appendix G.
	ZSUK	Zodiac Seats UK. Specialized in the production of business and first class seats. For more, see Appendix G.
	ZSFR	Zodiac Seats France. Develops and manufactures economy, business and first class seats, for both short and long haul. For more, see Appendix G.
	ZGEU	Zodiac Galleys Europe. Develops and produces narrow body galleys for mainly Airbus. For more, see Appendix G.
	ZAEE	Zodiac Aircatering Equipment Europe. Develops and produces trolleys and containers and is the biggest player in this field, supplying the majority of airliners and caterers. For more, see Appendix G.

12.2 **Anatomical position and orientation**

Medical descriptions for anatomical position and orientation (from MedicineNet (2017)):

Anterior	The front, as opposed to the posterior.
Anteroposterior	From front to back, as opposed to posteroanterior.
Caudad	Toward the feet (or tail in embryology), as opposed to cranial.
Caudal	Pertaining to, situated in, or toward the tail or the hind part. Or below another structure.
Cranial	Toward the head, as opposed to caudad.
Deep	Away from the exterior surface or further into the body, as opposed to superficial.
Distal	Further from the beginning, as opposed to proximal.
Dorsal	The back, as opposed to ventral.
Horizontal	Parallel to the floor, a plane passing through the standing body parallel to the floor.
Inferior	Below, as opposed to superior.
Inferolateral	Below and to one side. Both inferior and lateral.
Lateral	Toward the left or right side of the body, as opposed to medial.
Medial	In the middle or inside, as opposed to lateral.
Posterior	The back or behind, as opposed to the anterior.
Posteroanterior	From back to front, as opposed to anteroposterior.
Pronation	Rotation of the forearm and hand so that the palm is down (and the corresponding movement of the foot and leg with the sole down), as opposed to supination.
Prone	With the front or ventral surface downward (lying face down), as opposed to supine.
Proximal	Toward the beginning, as opposed to distal.
Sagittal	A vertical plane passing through the standing body from front to back. The mid-sagittal, or median plane, splits the body into left and right halves.
Superficial	On the surface or shallow, as opposed to deep.
Superior	Above, as opposed to inferior.
Supination	Rotation of the forearm and hand so that the palm is upward (and the corresponding movement of the foot and leg), as opposed to pronation.
Supine	With the back or dorsal surface downward (lying face up), as opposed to prone.
Transverse	A horizontal plane passing through the standing body parallel to the ground.
Ventral	Pertaining to the abdomen, as opposed to dorsal.
Vertical	Upright, as opposed to horizontal.

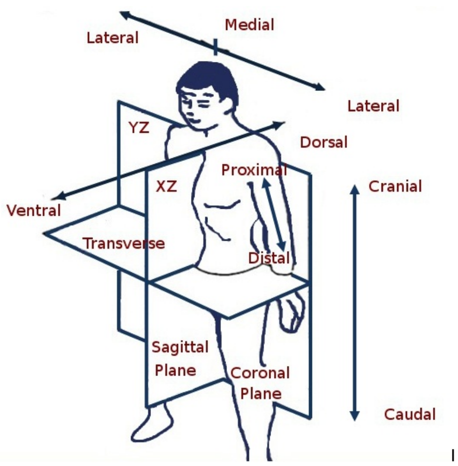


Figure 12.1 | Anatomical planes and orientation

12.3 Musculoskeletal anatomy

For further reading on muscle positions, Montgomery, Hislop, Connelly, and Daniels (2007): *Daniel's and Worthingham's muscle testing: techniques of manual examination* is recommended. For further reading on head, neck and eye anatomy, Paulsen and Waschke (2011): *Sobotta Atlas of Human Anatomy - Head, Neck and Neuroanatomy, Vol. 3, 15th ed.* is recommended. For a comprehensive overview of the human anatomy Standring (2015): *Gray's Anatomy: The Anatomical Basis of Clinical Practice* is recommended.

12.3.1 Neck muscles anatomy

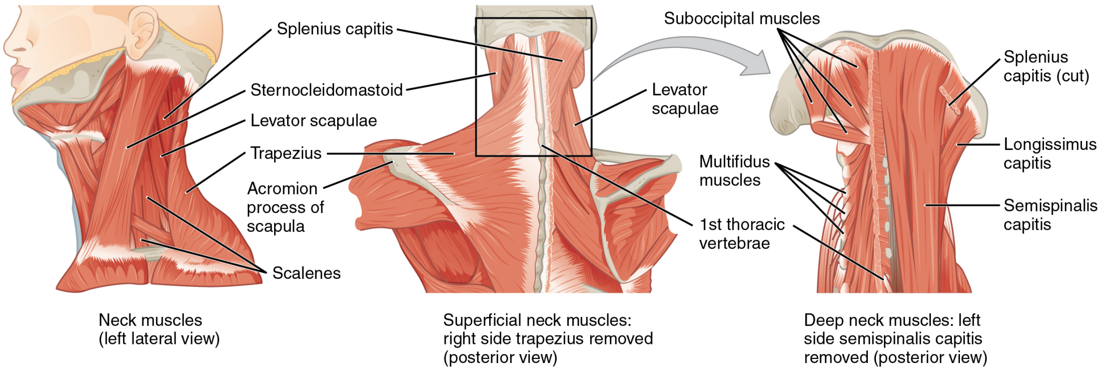


Figure 12.2 | Neck muscles

12.3.2 Eye muscles anatomy

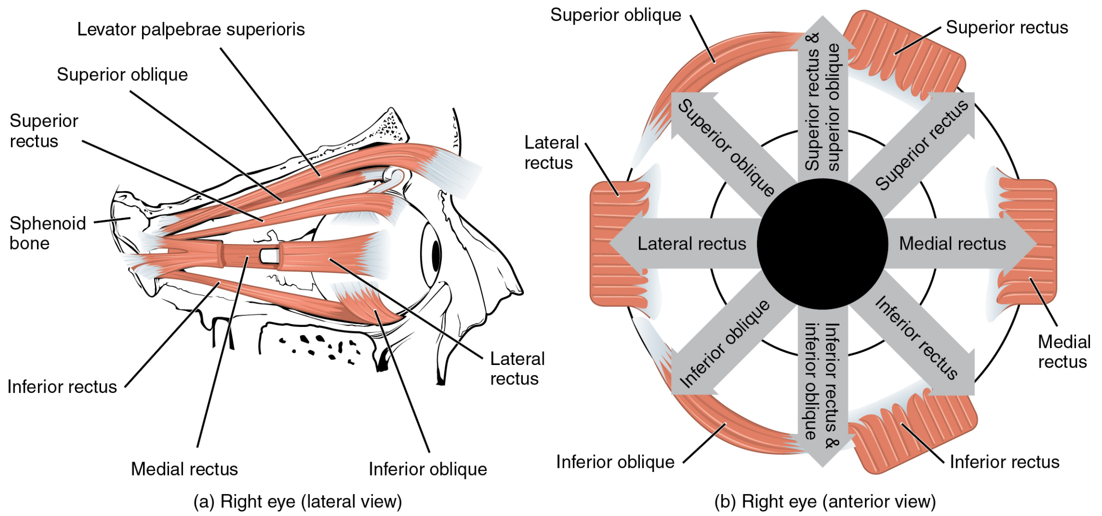


Figure 12.3 | Ocular muscles (based on Ansari and Nadeem (2016) and Remington (2012))

12.3.3 **Skull and cervical vertebrae anatomy**

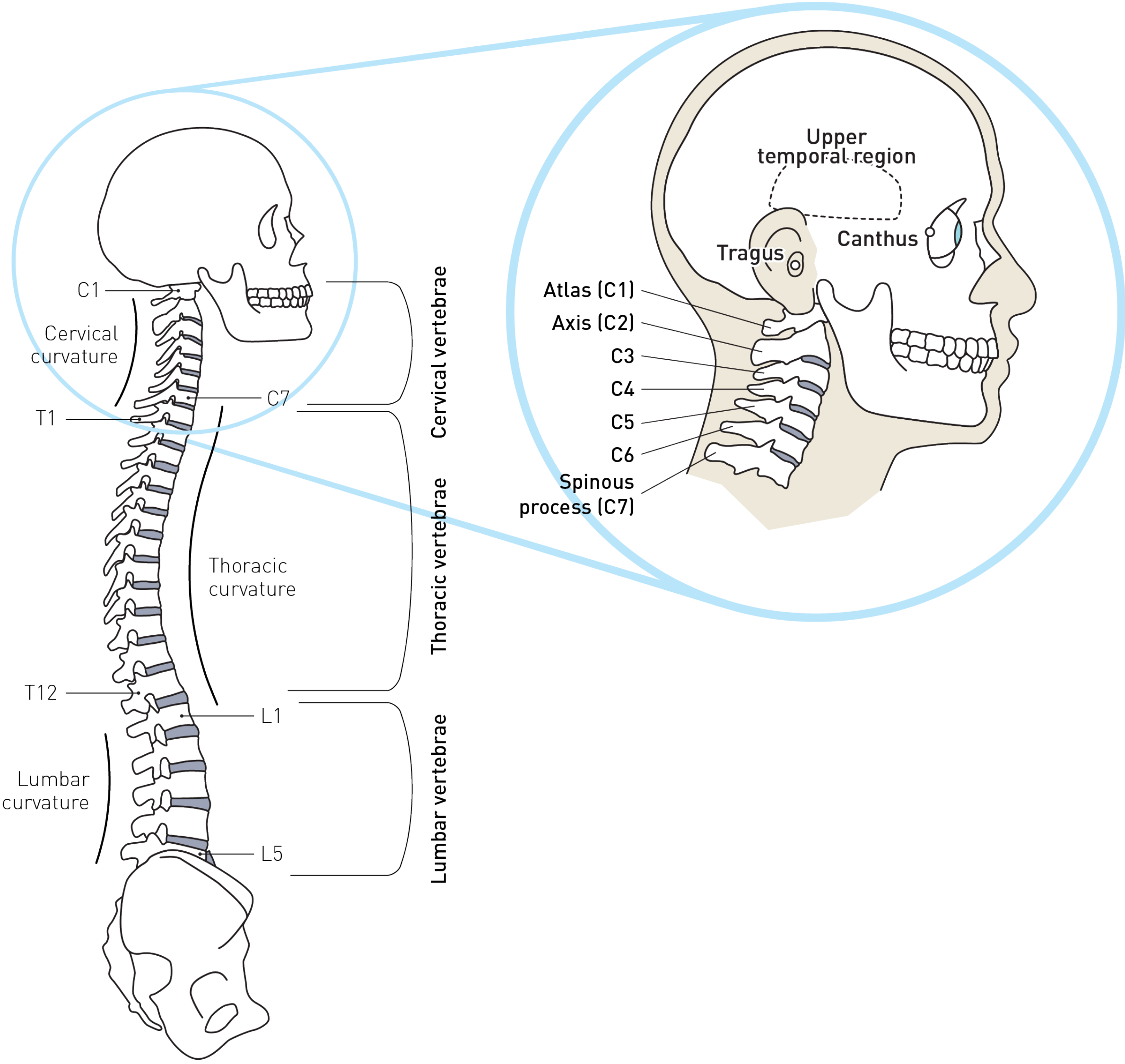


Figure 12.4 | Lateral view of the cervical vertebrae and skull (based on Paulsen & Waschke (2011) and Montgomery et al. (2007))

14

13 **Appendix**

Appendix A WORK paper: Comfort and pressure distribution in a human contour shaped aircraft seat (developed with 3D scans of the human body)

This study was published in WORK of IOS press in 2016, based on an AED study by K. Berghman, M. Koenraads, J.A. Kane, K. Krishna, T.K. Carter and M. Smulders, with advice and support of P.Vink, U. Schultheis and R. van der Horst, and an additional comfort study by K. Berghman, P. Vink and M. Smulders, with advice and support of U. Schultheis.

Comfort and pressure distribution in a human contour shaped aircraft seat (developed with 3D scans of the human body)

M. Smulders[a*], K. Berghman[a], M. Koenraads[a], J.A. Kane[a], K. Krishna[a], T.K. Carter[a], U. Schultheis[b] and P. Vink[a]

[a] Faculty of Industrial Design Engineering, Delft University of Technology, Landbergstraat 15, 2628CE Delft, The Netherlands

[b] Human Factors and Ergonomics, Zodiac Seats U.S. LLC, 2000 Weber Drive, Gainesville, Texas 76240, United States of America

* Corresponding author. E-mail address: info@maximsmulders.com

---

Abstract

BACKGROUND: The concept of comfort is one way for the growing airline market to differentiate and build customer loyalty. This work follows the idea that increasing the contact area between human and seat can have a positive effect on comfort [5, 6, 7].

OBJECTIVE: To improve comfort, reduce weight and optimise space used, a human contour shaped seat shell and cushioning was developed.

METHODS: First the most common activities, the corresponding postures and seat inclination angles were defined. The imprints of these postures on a rescue mat were 3D scanned and an average human contour curve was defined. The outcome was transferred to a prototype seat that was used to test the effect on perceived comfort/discomfort and pressure distribution.

RESULTS: 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 subjects' buttocks and the seat pan over a traditional seat.

CONCLUSIONS: This study shows that it is possible to design a seat pan and backrest based on the different contours of study subjects 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; additionally 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. Keywords: Lightweight, 3D scanning, aircraft seat, comfort, pressure distribution

Keywords: Lightweight, 3D scanning, aircraft seat, comfort, pressure distribution

---

1. Introduction

The average 5.6% growth of passenger demand (Passenger Revenue Kilometers) over the last 10 years, as estimated by IATA [1], creates opportunities for airlines. By understanding the passengers' flight selection behaviour and developing products and services fitting the selection behavior, airlines can increase passenger revenue [2].

Brauer [2] 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 80s, passenger comfort was a key variable for passenger satisfaction andwillingness to use the airline again [3]. 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 [4], 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 [5,6] 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 comfort/discomfort of subjects. Additionally, Franz et al. [8] showed a method for developing a contour based seat in order to increase and subsequently improve the contact area.

These studies [5,6,8] 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 human contour could improve pressure distribution and accordingly increase comfort and decrease discomfort perception. However, these studies are all focused 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 airlines revenue by attracting more passengers, revenue could also increased by reducing fuel consumption, which has a positive effect on the environment too [9]. Making a seat which better fits the human contour could result in the reduction of required seat materials and thereby weight [8], which contributes to the reduction of the aircraft's fuel consumption. However, the question is: what is the effect of this lightweight 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 lightweight 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 focused on long haul flights, since long haul flights are most challenging in terms of comfort.

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 and confirmed by literature [10, 11]. 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 [12] showed that these could be different entities when studying a seat.

2.1. Inclination for different activities in Business Class aircraft seats

2.1.1. Subjects

In the first study ten Dutch adults participated. Care was taken to select subjects with a variety of height and weight. Five female and five male subjects participated (Table 1). All subjects frequently flew by plane and two were accustomed to travelling business class.

Table 1
Anthropometric measurements of subjects

		Mean	SD
Male (n=5)	Age [years]	21	1.2
	Stature [cm]	184	10.6
	Body weight [Kg]	74.8	7.9
Female (n=5)	Age [years]	21.8	1.6
	Stature [cm]	170.4	8.2
	Body weight [Kg]	62.4	5.3

2.1.2. Stimuli

A realistic setting was created by using business class seats placed in a partial airplane cabin with two actors (Fig. 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 degree angle to simulate the standard inclination of an airplane during flight at cruising altitude (angle of attack). The pitch was set at 60 inches (~1.52 metres) (Fig. 2), as is standard in business class. Furthermore, subjects were provided with hand luggage containing a questionnaire, laptop, magazines, one book, a pen, a sleeping mask and headphones. These objects were used to simulate different activities in a realistic manner. Subjects were also provided with food and drinks during the simulated flight by an actor (the flight attendant).

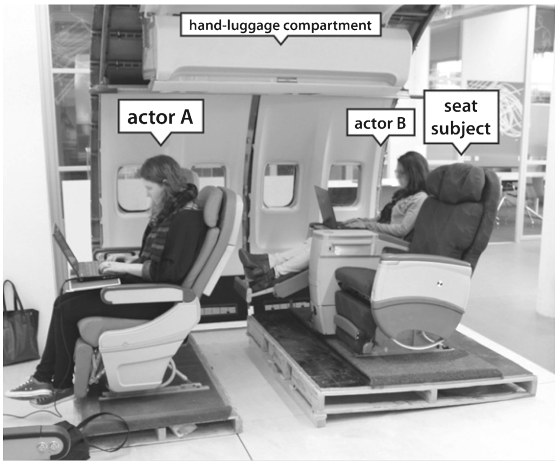


Fig. 1. Partial airplane cabin with two actors.

Fig. 2. Inclination angle and pitch length.

2.1.3. Apparatus

Two cameras were used to capture every posture (Fig. 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.

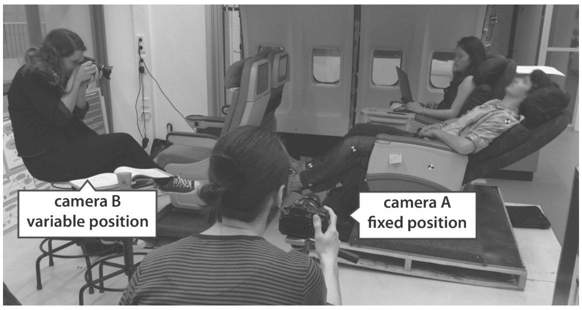


Fig. 3. Camera positions.

2.1.4. Procedure

Subjects were first asked to experience the adaptability of the seat for a couple of minutes. During this activity, the subjects 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 subjects found a comfortable position and inclination, they mentioned this to the researcher and a picture was taken with both cameras. The subjects 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, height, 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 subjects 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, subjects 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.

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 and confirmed by literature [13, 14].

2.2. 3D scanning the human contour in pre-determined inclinations

2.2.1. Subjects

In the second study twelve Dutch adults participated. Care was taken to select subjects with a large variety in stature height, weight and age. Six female and six male subjects participated (Table 2).

Table 2
Anthropometric measurements of subjects

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

2.2.2. Apparatus

A test seat was built with an adjustable leg rest and backrest inclination angles. A rescue mat (further referred to as mat) was positioned on the test seat (Fig. 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. The 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.

Fig. 4. Rescue mat in test seat.

2.2.3. Procedure

At first subjects laid down upon the mat, which was positioned horizontally. Then the leg rest and backrest were inclined by two researchers (Fig. 5) to a predetermined inclination (Table 3), based on the findings of the study described in §2.1 (results can be found in §3.1).

Subjects 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 subject left the seat and the imprint was 3D scanned.

After the 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 subject, in the three set postures; active, passive and sleeping.

Fig. 5. Backrest being inclined by two researchers

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

2.2.4. Measures

All imprints were individually 3D scanned and meshed. In Rhinoceros 3D a grid with fixed dimensions (seatpan 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 Fig. 6). To ensure each grid was projected from the same origin, vertical metal pins on the seat (Fig. 7) were reference points, for alignment of all scans.

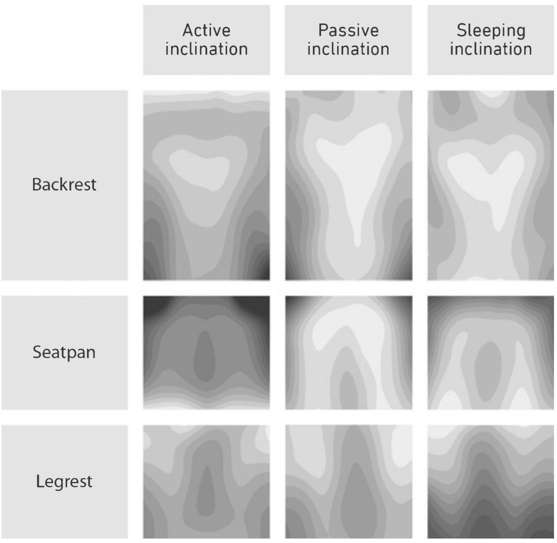


Fig. 6. Height map projection of the backrest, seat pan and leg rest of one subject.

Fig. 7. Reference pins on test seat, covered by socks for safety.

2.3. Pressure distribution calculations and testing for cushioning

Since postural change is important for decreasing discomfort during prolonged sitting [15], it is important 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 are, but it impedes movement.

Since the seat's shell (in this design) is a single curved 2D shape (see §2.4), the 3D human contour is achieved by varying the firmness of the cushioning.

The thickness of the cushioning was set to 30 mm, for the purpose of weight and space reduction. The new cushioning is relatively thin compared to the traditional cushioning of 85-139 mm. The firmness needed for the cushioning to create the average human 3D curve was calculated with the help of the ideal pressure distribution [7] and validated using a theory for calculating cushion indentation [16]. The ideal pressure distribution avoids pressure peaks on softer tissues of the body since this is more healthy [16]. For calculation purposes, the unit IFD was used. IFD represents the Indentation Force Deflection, which is the force needed to indent the material a certain percentage of its original thickness.

The input for calculating the IFD is the force on the cushioning and the desired indentation of the cushioning. The force was calculated [17] based on the pressure distribution as represented by Zenk et al. [8] (Fig. 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 §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 [18]. The different masses per body area were translated into the resulting force per grid square to check the calculations.

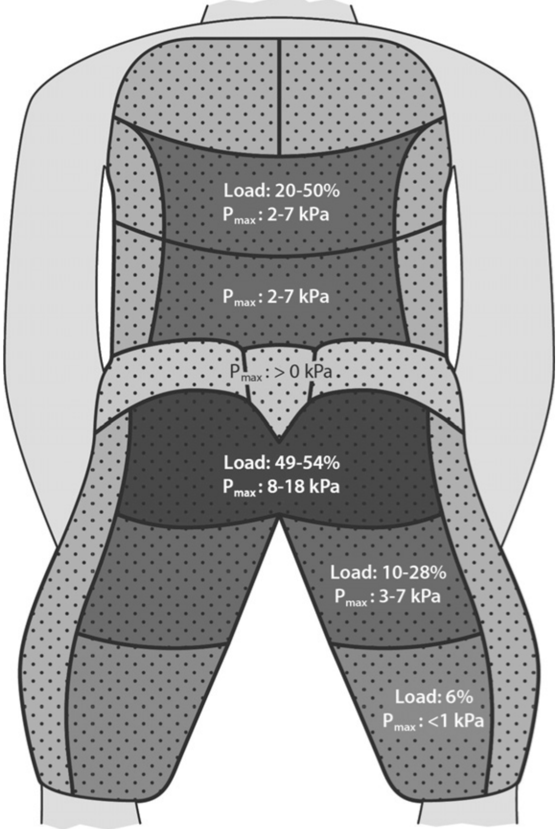


Fig.8. PressuredistributionasdescribedbyVinkandBrauer[18].

Based on the calculated firmnesses, cushioning was prototyped by using different firmnesses of AMES DISTO® Spacer Fabric (Fig. 9). The comfort of the cushioning on the shell was optimised using a trial and error validation test. Twelve subjects sat on the seat for five minutes (Fig. 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 (Fig. 11). The cushioning was adjusted and the test repeated until the subjects rated the cushioning as satisfactory.

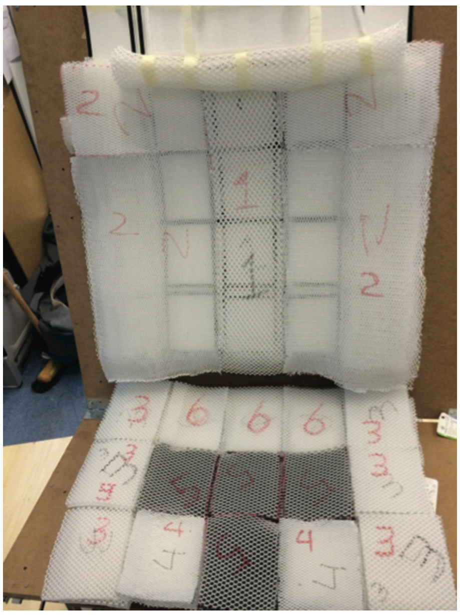


Fig. 9. Prototyped cushioning.

Fig. 10. Trial and error test.

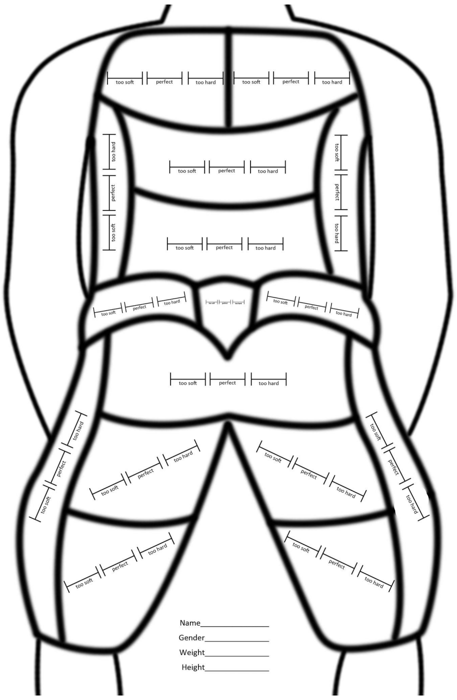


Fig. 11. LPD like form.

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 retardent qualities, density and strength. Because the cushioning was more firm 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 §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 10.25 kg per seat, thanks to the use of lower density and less materials (–9.9 kg), lighter cushioning (–1.1 kg) and the change to thicker breathing fabric (+0.75 kg). However, extra weight can be expected since the prototype does not meet the strict aviation safety and crash regulations.

2.5. *Comfort and discomfort effects of the prototype and traditional seat*

2.5.1. *Subjects*

Twenty people participated in the third study. Care was taken to select subjects with a variety in stature height, weight and age. Ten female and ten male subjects participated (Table 4).

Table 4

Anthropometric measurements of subjects

		Mean	SD
Male (n=5)	Age [years]	31.6	21.2
	Stature [cm]	182.4	10.9
	Body weight [Kg]	83.6	17.0
Female (n=5)	Age [years]	31.6	13.2
	Stature [cm]	172.7	8.6
	Body weight [Kg]	78.0	14.5

2.5.2. *Apparatus*

A prototype seat was built with the 2D curved shell and the cushioning, as described in §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 degree inclined backrest, an 8 degree inclined seat pan, a 20 degree inclined leg rest and a footrest perpendicular to the leg rest (all including a 3 degree inflight inclination). The inclination resembled the active position as determined in §2.1. This posture was selected since it causes the highest pressure points on the seat and is therefore 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 (Fig. 12). Two small tables, headphones, food and drinks were provided. Furthermore human measures were taken using an anthropometer, an adjustable measuring seat and a digital scale.

Fig. 12. Test set up.

2.5.3. *Procedure*

Prior to the study, subjects 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.

Subjects were seated in pairs (to prevent order effects) and experienced each seat for 90 minutes. Each pair of subjects 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 §2.6 and take anthropometric measurements of the subjects, such as weight, stature length and hip width. Furthermore the subjects had a chance to walk and use the toilet before switching seats for the other 90 minutes of sitting. The subjects 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 subjects described their overall comfort on a 0–5 Likert scale and every 30 minutes the subjects completed a LPD form (see Fig. 13). Subjects were requested not to leave the seat during the 90 minutes. Drinks and snacks were offered.

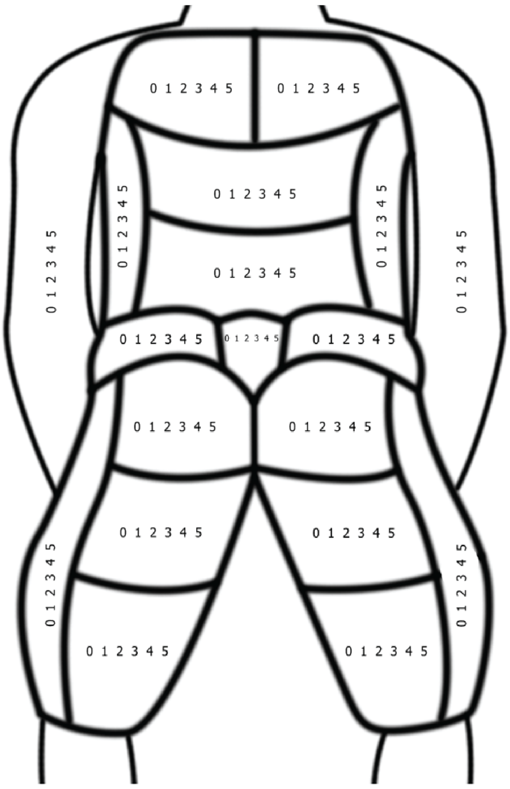


Fig. 13. LPD form.

2.5.4. Measures

All comfort and discomfort ratings per seat were compared over time and per seat using Microsoft Excel and SPSS. Because comfort values are not normally distributed, the Wilcoxon test was used in addition to a *t* test, to look for differences between the prototype and the traditional seat. The significant differences between total comfort and discomfort score were calculated ($p < 0.05$), and also between regions in the body (buttock and low back).

2.6. Pressure distribution effects of the prototype and traditional seat

2.6.1. Subjects

Pressure distribution of the prototype and traditional seat was recorded using the same subjects from §2.5.1.

2.6.2. Apparatus

The same test set up with two seats as mentioned in §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.

2.6.3. Procedure

During the break described in §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 subjects sat in the seat on the mat for 5 minutes for posture settlement [19]. Then the pressure distribution was recorded.

2.6.4. Measures

With the FSA software the pressure in kiloPascals (kPa) per cell was determined. Coloured images 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 area 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 ($p < 0.05$).

3. Results

3.1. Inclination for different activities in Business Class aircraft seats

The results of the mean angles and standard deviation (SD) of the backrest inclination of the experiment described in §2.1 are shown in Table 5 and of the leg rest inclination in Table 6.

Plotting the results graphically (see Fig. 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.

When combining all measures, three main business class inclinations were determined (backrest mean ± SD, leg rest ± SD): Cluster #1 (active) with $22.8^\circ \pm 6.8$, $20.3^\circ \pm 20.3$, Cluster #2 (passive) $31.0^\circ \pm 7.7$, $48.1^\circ \pm 17.5$ and Cluster #3 (sleeping) $55.5^\circ \pm 0.6$, $63.1^\circ \pm 2.3$. These three inclination clusters were used in the ‘3D scanning the human contour in predetermined inclinations’ study, as described in §2.2. Comparing the results with literature [12, 13] showed similarities. Kilincsoy et al. [13] described an active posture with a 105° trunk thigh angle, confirming this studies active inclination angle. Park et al. [14] describe a 117° trunk thigh angle, similar to this studies passive inclination angle.

Table 5
Backrest angles in degrees (n=10, except 'Listening to music') with respect to the vertical

	Angles backrest in degrees (incl. 3 deg. airplane angle)							
	Write	Eat and drink	Sleep	Watch Flight Entertainment System	Listen to music (n=6)	Play/work on mobile phone/tablet	Read book	Work on notebook
Mean	20,5°	20,4°	55,5°	31,7°	36,3°	31,3°	30,2°	27,5°
SD	5,5°	5,0°	0,6°	5,6°	11,3°	7,6°	6,4°	7,6°

Table 6
Leg-rest angles in degrees (n = 10, except 'Listening to music') with respect to the vertical

	Angles leg-rests in degrees (incl. 3 deg. airplane angle)							
	Write	Eat and drink	Sleep	Watch Flight Entertainment System	Listen to music (n=6)	Play/work on mobile phone/tablet	Read book	Work on notebook
Mean	28,5°	37,9°	63,1°	50,0°	51,0°	43,4°	49,0°	42,1°
SD	19,1°	22,1°	2,3°	20,2°	14,7°	20,3°	14,9°	19,2°

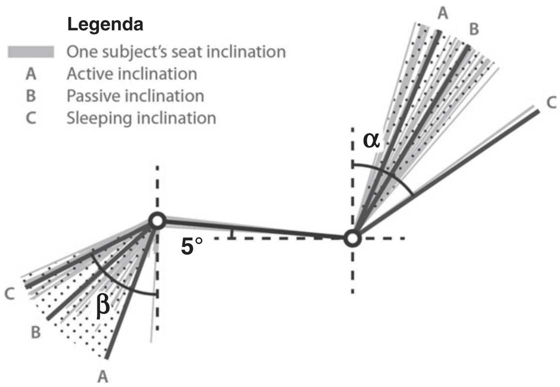


Fig. 14. Plotted inclination angles.

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 (Fig. 15). These surfaces were used in §2.4.

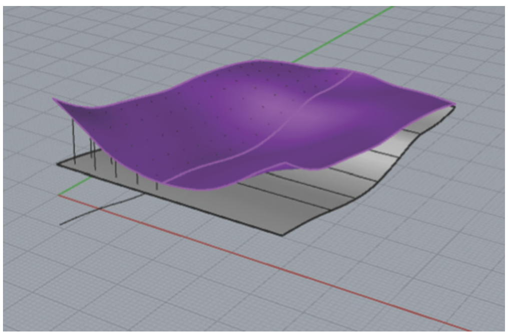


Fig. 15. Average point grid of the seat pan.

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 × 50 mm, can be found in Tables 7 and 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 firmnesses 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 out of separate pieces of different thicknesses and firmnesses (Fig. 16), which were sewn together into one layered cushion. To limit the influence of the seams on the cushion properties, but at the same be small enough to create the ideal pressure distribution based cushioning, block sizes of 140 × 165 mm were used.

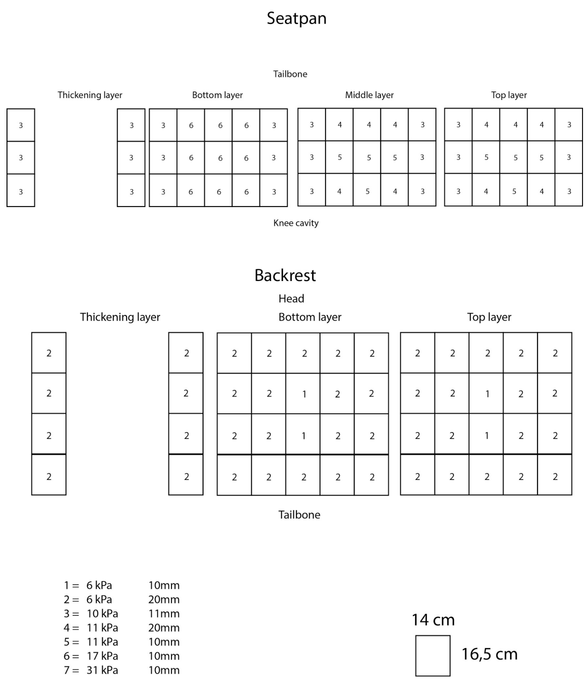


Fig. 16. Final firmnesses cushioning.

Table 7 IFD values backrest in Newton per mm

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 8 IFD values seat pan in Newton per mm

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

Table 9
Values of discomfort within the seat compared (n = 20)

	Time	30 minutes		60 minutes		90 minutes	
	Seat type	A	B	A	B	A	B
Average overall discomfort	Mean	3.9	6.2	8.1	6.55	7.9	9.65
	Standard deviation	2.31	4.74	6.27	4.41	8.40	5.84
	p-value (T-test)	0.073		0.383		0.361	
Lower back discomfort	Mean	1	1.7	3.15	3.4	2.45	3.65
	Standard deviation	1.03	1.63	2.83	3.93	2.28	2.81
	p-value (T-test)	0.044		0.783		0.114	
Seat discomfort	Mean	1.5	2.35	3.3	2	3.6	4.05
	Standard deviation	1.88	2.96	5.32	2.20	5.76	5.35
	p-value (T-test)	0.204		0.265		0.640	

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.

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 in the existing seat (seat A) and the prototype (seat B).

Regarding the discomfort calculated with the LPD forms, there was a significant difference in discomfort between seat A and seat B (see Table 9). Seat B shows significantly more overall discomfort than seat A after 30 minutes of sitting (p = 0.007). This effect diminished after 60 and 90 minutes, thus there was no significant discomfort after 60 and 90 minutes in seat A or B. Studying the discomfort of seat A and B in the different body areas, lower back and the buttock, the only significant difference found was the lower back after 30 minutes. Seat B caused significantly higher discomfort than seat A in the lower back after 30 minutes (p = 0.04). There was no significant difference in seat A and B for the discomfort in the buttocks.

The significance in change of overall discomfort over time is found in Table 10. There was a significant increase in discomfort in seat A during the period of 30 to 60 minutes in the seat (p = 0.04). Furthermore the discomfort significantly increased in the period after 30 minutes of sitting until 90 minutes of sitting in seat A (p = 0.03). The discomfort in seat B significantly increased in the period from 30 until 90 minutes of sitting (p = 0.0007). Thus the discomfort in seat A and in seat B significantly increased over the period of 30 to 90 minutes of sitting. Only in seat A was there a significant increase of discomfort in the period between 30 and 60 minutes of sitting.

Table 10
Difference in discomfort at different times within same seat (n=20)

	Seat A	Seat B
Values compared (minutes)	p-value (T-test)	p-value (T-test)
30 – 60	0.004	0.817
60 – 90	0.913	0.054
30 – 90	0.025	0.0007

Table 11
Values of comfort within the seat compared (n = 20)

	Time in seat in minutes	15	30	45	60	75	90
Seat A	Mean comfort score	4.25	4.15	4	3.65	3.6	3.5
	Standard deviation	0.55	0.59	0.46	0.75	0.68	0.83
Seat B	Mean comfort score	4.00	3.90	3.60	3.50	3.35	3.45
	Standard deviation	1.17	1.10	1.16	1.11	1.08	1.15
	p-value difference A and B (T-test)	0.135	0.204	0.057	0.505	0.286	0.858

The difference in comfort in seat A and seat B are found in Table 11. There was no significant difference of comfort in seat A or B at anytime. The comfort in seat A decreased significantly over time (see Table 12) in the period from 45–60 minutes ($p = 0.015$) and in the seat and during the overall period from 15 to 90 minutes in the seat ($p = 0.009$). The comfort in seat B decreased significantly over time in the period from 30–45 minutes ($p = 0.010$) in the seat and during the overall period from 15 to 90 minutes in the seat ($p = 0.012$). Thus the comfort in both seat A and seat B significantly decreased in the period from 15 to 90 minutes of sitting. In seat A there was a significant decrease in comfort in the period from 45–60 minutes of sitting, in seat B this decrease occured in the period from 30–45 minutes of sitting.

Table 12

Difference in comfort at different times within same seat ($n = 20$)

	Seat A	Seat B
Values compared (minutes)	p-value	p-value
15-30	0.428	0.428
30-45	0.083	0.010
45-60	0.015	0.428
60-75	0.716	0.186
75-90	0.330	0.330
15-90	0.009	0.012

3.6. *Pressure distribution effects of the prototype and traditional seat*

The mean pressure of the seat pan of seat A mean ± SD was 6.0 ± 1.4 [kPa/cell] and seat B mean ± SD of 4.8 ± 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 1.2 ± 0.4 [kPa/cell] and seat B mean ± SD of 2.5 ± 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 ± 23.5 [cells] and for seat B 123.0 ± 18.5 [cells], was also significant ($p < 0.001$).

The number of recorded contacts of the backrest for seat A was 73.8 ± 25.9 [cells] and for seat B 50.6 ± 14.4 [cells], was also significant ($p < 0.001$). This means that the contact area in seat A was larger than in seat B for both the seat pan and the backrest.

4. Discussion

4.1. *Inclination for different activities in Business Class aircraft seats*

During the inclination study, it was noted that subjects did not always change their inclination when conducting another activity. As subjects 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 et al. [20]. The effect of this on the resulting inclination preferences was not further investigated, but it could have disturbed the results. Subjects 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. It is therefore recommended to incline the test seat back into a standard position after each performed activity in further research.

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 §2.2.4 vertical metal pins on the seat (Fig. 7) were used as reference points, to align all 3D scans. This however was not ideal, because subjects 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 Mastrigt [21] did in the YZ-plane.

Franz et al. [8] 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 to comfort.

Apparently a one-to-one translation from scan to seat is not possible for groups of users. A one-toone 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. [8] showed that in the neck less pressure was acceptable than on the back of the head. Zenk et al. [7] 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 [10]. 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 [22]. This means that a 3D scan is helpful for the design, but a creative step to translate it into a product is still needed. At this time it is unclear what the best procedure would be to make this step.

The approach used in this study is effective, but Franz et al. [8] show another possibility of measurement. Franz et al. suggested using inflatable cushioning, which is made out 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 subjects only, who are rather tall compared to an international audience [24]. It is therefore recommended to take the audience (e.g. international, children) into account when selecting subjects for gaining a representative average or ideal curve.

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 adressed. As the cushioning on the sides of the seat are 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 firmnesses of the cushioning, some assumptions were made. First of all, the ideal pressure distribution as described by Vink and Brauer [18] was projected onto the seat. As the exact sizes of the pressure distribution, supports on the size of the subject, the pressure distribution was simplified in 3 equally sized area's; the buttocks, the thighs and the knee cavities. Secondly the seat pan and backrest were divided into a 50 × 50 mm 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 Vink and Brauer [18] was not detailed enough to make more precise calculations. Additionally, the used cushioning did not allow for smaller squares.

4.4. Prototyping business aircraft seat based on the human contour

The prototype used during the study as described in §2.5 was supported by a wooden frame, which was not adjustable and the foot rest was not attached to the seat. Therefore the prototype was different from the traditional seat, as the traditional seat had an adjustable foot rest attached to the leg rest. Although one subject assumed the traditional seat was the newly developed seat, it can be questioned whether subjects 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 subjects' visual interpretation having an influence on their perceived comfort and discomfort.

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 statistical results, only interpretations. There is no significant difference, which might lead to the conclusion that reducing the weight is possible without large effects on comfort.

The cushioning of the prototype was 30 mm thick and the cushioning of the traditional seat was to 85139 mm thick in the seat pan and 133 mm thick in the backrest. Thus the contour based seat was 65-79% thinner in the seat pan and 73% thinner in the backrest than in the traditional seat. The thickness of the backrest has a direct effect on the pitch length; the new backrest design is 83 mm thinner. Valuable space was saved whilst the same level of comfort was obtained. This has also been described for car seats [8,9]. However, there is more discomfort at the beginning of the test (after 30 minutes) in the lower back, which was so large that it influenced the total discomfort. Later, the difference between the two seats was not significant anymore. Ahmadpour et al. [4] 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 optimize the seat form or cushioning, to improve the experience in the first 30 minutes.

4.6. Pressure distribution effects of the prototype and traditional seat

The pressure distribution showed (see §3.6) the pressure was better distributed in the seat pan, but less in the back in the prototype seat. Literature shows that a lower average pressure is accompanied by less discomfort (e.g. Noro et al. [23]). However, this is not affirmed in this paper, 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.

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 transform it to curvature and cushioning. 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 lightweight human contour shaped business class aircraft seat did not affect the comfort, discomfort and pressure distribution when compared with 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 the lightweight human contour based seat has a potential to achieve the same comfort and discomfort effects as a traditional business class seat.

Acknowledgments

We want to thank our colleagues who helped with 3D scanning the human contour and processing the results; A. Vogel, J.A. Stewart, A.J. Weiss, L.J. Lam, A.L.E. de Vries, S.H.F. van Gils. Staff of the Delft University of Technology, for their help, advice and/or guidance in this project; Prof.dr. P. Vink, B.J. Naagen, 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. Special thanks to F. Lee, S. Does and Zodiac Seats US LLC, for supporting this research and design project. H. Albers and Royal TenCate NV for supplying fiber materials and J. Berning and Ames Europe BV for supplying cushioning. R. Ko¨nemann 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.

Conflict of interest

The authors have no conflict of interest to report.

References

[1] International Air Transport Association. *Strong Demand for Air Travel Rises in 2014*. www.iata.org/pressroom/ pr/Pages/2015-02-05-01.aspx (accessed 14-05-15).

[2] Brauer K. Convenience, comfort, and costs. Presentation at the aircraft interior EXPO; 2004.

[3] Richards LC. On the psychology of passenger comfort. Human Factors in Transport Research (Based on the Proceedings of the International Conference on Ergonomics and Transport) 1980;2:15-23.

[4] Ahmadpoura N, Lindgaard G, Roberta JM, Pownalld B. The thematic structure of passenger comfort experience and its relationship to the context features in the aircraft cabin. Ergonomics 2014;57(6):801-15.

[5] Zemp R, Taylor WR, Lorenzetti S. Are pressure measurements effective in the assessment of office chair comfort/discomfort? A review. Applied Ergonomics 2015;48:273-82.

[6] De Looze MP, Kuijt-Evers LF, van Dieen J. Sitting comfort and discomfort and the relationships with objective measures. Ergonomics 2003;46:985-97.

[7] Zenk R, Franz M, Bubb H, Vink P. Technical note: Spine loading in automotive seating. Applied Ergonomics 2012;43:290-5.

[8] Franz M, Kamp I, Durt A, Kilincsoy U, Bubb H, Vink P. A light weight car seat shaped by human body Contour. Int J Human Factors Modelling and Simulation 2011;2(4):31426.

[9] Vink P, Franz M, Kamp I, Zenk R. Three experiments to support the design of lightweight comfortabel vehicle seats. Work 2012;41:1466-70.

[10] Greghi FM, Rossi NT, Souza GBJ, Menegon LN. 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 2012;41(SUPPL.1):5560.

[11] Kamp I, Kilincsoy U, Vink P. Chosen postures during specific sitting activities. Ergonomics 2011;54(11):1029-42.

[12] Helander MG, Zhang L. Field studies of comfort and discomfort in sitting. Ergonomics 1997;40:895-915.

[13] Kilincsoy U, Wagner AS, Bengler K, Bubb H, Vink P. Comfortable rear seat postures preferred by car passengers. Based on the Proceedings of the 5th *International Conference on Applied Human Factors and Ergonomics* 2014;20:823-31.

[14] Park SJ, Kim CB, Kim CJ, Lee JW. Comfortable driving postures for Koreans. International Journal of Industrial Ergonomics 2000;26:489-97.

[15] Fujimaki G, Noro K. Sitting comfort of office chair design. In Proceedings of the 11th International Conference on Human–Computer Interaction 2005;22-7.

[16] Goossens RHM. Biomechanics of Body Support, PhD thesis. Rotterdam, the Netherlands: Erasmus Universteit; 1994.

[17] Chow WW, Odell EI. Deformations and stresses in soft body tissues of a sitting person. Journal of BiomechanicalEngineering 1978;100(2):79-87.

[18] Vink P, Brauer K. Aircraft Interior Comfort and design. Boca Raton, USA: CRC Press; 2011

[19] Kyung G, Nussbaum MA. Driver sitting comfort and discomfort (part II): Relationships with and prediction from interface pressure. International Journal of Industrial Ergonomics 2008;38:526-38.

[20] Helander MG, Little SE, Drury CG. Adaptation and sensitivity to postural change in sitting. Human Factors: The Journal of the Human Factors and Ergonomics Society 2000;42:617-29.

[21] Hiemstra-van Mastrigt S. Comfortable passenger seats: Recommendations for design and research [PhD Thesis]. Case study: Developing an ideal aircraft seat contour using 3D scanning techniques. Delft: Delft University of Technology; 2015. p196-210. Available from: repository. tudelft.nl/view/ir/uuid%3Aeedd25e6-c625-45e9-9d32f818aa89c19d/

[22] Groenesteijn L, Hiemstra-van Mastrigt S, Gallais C, Blok M, Kuijt-Evers L, Vink P. Activities, postures and comfort perception of train passengers as input for train seat design. Ergonomics 2014;57(8):1154-65.

[23] Noro K, Naruse T, Lueder R, Nao-i N, Kozawa M. Application of zen sitting principles to microscopic surgery seating. Applied Ergonomics 2012;43(2):308-19.

[24] Molenbroek JF. DINED, Anthropometric database: Delft University of Technology; 2004. Available from: dined.io.tudelft.nl.

Appendix B ICC2017 conference paper: Neck posture and muscle activity with and without head support in a reclined sitting posture when watching IFE

This conference paper was presented the 18th of June 2017 at the 1st International Comfort Congress in Salerno, Italy.

Neck posture and muscle activity with and without head support in a reclined sitting posture when watching IFE

M. Smulders[12*], A. Naddeo[3], N. Cappetti[3], E.D. van Grondelle[1], U. Schultheis[2] and P. Vink[1]

[1] Faculty of Industrial Design Engineering, Delft University of Technology, Landbergstraat 15, 2628CE Delft, The Netherlands

[2] Human Factors and Ergonomics, Zodiac Seats U.S. LLC, 2000 Weber Drive, Gainesville, Texas 76240, USA

[3] Department of Industrial Engineering, University of Salerno, Via Ponte don Melillo, 1, 84084 Fisciano, SA, Italy

* Corresponding author. Tel.: +31 6 29 488 202. E-mail address: info@maximsmulders.com

Abstract In designing a headrest it is important to define the ideal head position and neck angle. There is literature on the ideal head position, but not in the context of watching IFE in a business class aircraft seat. In this study (n=21) the neck muscle activity (EMG), expected long-term comfort and head/neck inclination were studied in a reclined position (as is possible in business class) when watching IFE in the condition of with and without head/neck support.
It appeared that there were no significant differences in EMG between both conditions. However, the posture was significantly different; without head support by a headrest the head was found to be more upright. Expected long-term comfort was rated highest in the condition with a headrest.
The fact that no difference was found in EMG indicates that humans tend to look for a head position that is neutral, in the sense of minimal (muscle) effort. Head support in a reclined position may have a positive psychological effect on the user.

Keywords: EMG, posture, neck angle, aircraft seat, neutral head position, headrest

1 Introduction

In designing a headrest it is important to define the ideal head position and neck angle. There is literature on the ideal head position with an upright or slightly reclined trunk, of which an overview can be found in Table 1. However, for a situation in which the trunk is reclined the literature is limited. For the position in the car e.g. Park, Kim, Kim, and Lee (2000) and Kilincsoy, Wagner, Bengler, Bubb, and Vink (2014) presented comfortable angles, van Veen, Hiemstra-van Mastrigt, Kamp, and Vink (2014) even in the context of tablet use, but for a more reclined position that can be found in a business class aircraft seat when watching in flight entertainment (IFE) the ideal neck position is not described.

As observed in studies by van Rosmalen, Groenesteijn, Boess, and Vink (2009), van Rosmalen, Groenesteijn, Boess, and Vink (2010), C. S. S. Tan, Van den Bergh, Schöning, and Luyten (2014), Meziat Filho, Coutinho, and 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 IFE during flight. 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. 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. A possible explanation for this preference may be the lower back muscle activity in such a slouched posture (Goossens, Snijders, Roelofs, & Buchem, 2003) and lower pressure on the inter-vertebral disks (Wilke, Neef, Caimi, Hoogland, & Claes, 1999).

Table 1. The comfortable (neutral) head position (as described in Vink (2016)). See Figure 1 for a visual explanation of the given angle.

Reference	*n*	*Craniocervical angle (α)*
Raine and Twomey (1997)	160	41,1°
Johnson (1998)	34	40,4°
Ankrum and Nemeth (2000)	24	43,7°
van Veen et al. (2014)	10	41,2°

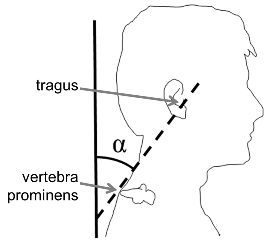


Figure 1. The craniocervical angle (α) between a line through the tragus and vertebra prominens (C7) and the vertical line (from Vink (2016))

1.1. Head flexion and the strain on the muscles

The head angle is – besides the orientation of the trunk – influenced by the viewing angle on the IFE screen. "The preferred line of sight becomes lower as the viewing distance decreases" (as cited in Ankrum and Nemeth (2000), and also been shown by Kroemer and Hill (1986)), indicating that in the economy class (where space is more scarce) an IFE screen should be below eye level and oriented perpendicular to the line of sight. Yoichi et al. (2012) states however, that a more horizontal line of sight is preferred for further distances of TV screens, and thus is more appropriate for business class with it's bigger screens, generous space (bigger eye-screen distance) and generous backrest recline.

When reclining (32-41°) in a business class seat while watching IFE, the passenger may flex their head forward with respect to the trunk without head/neck support for a prolonged period of time (e.g. when watching one or multiple movies) to establish a good (horizontal) view on the IFE screen (see Figure 2), which was observed in the study by Smulders et al. (2016). However, prolonged (unsupported) neck flexion beyond 30° could lead to severe muscle fatigue and discomfort according to Chaffin (1973). This may result in pain and spasm in the neck muscles, which can lead to headache and pains of the head, face and behind the eyes (Dalassio, 1980; J. Travell, 1967; J. G. Travell & Simons, 1992).

In the studies of van Rosmalen et al. (2009) and Smulders et al. (2016) it was observed that participants lacked neck/head support when watching TV/IFE in the slouched posture. In the study by Hiemstra-van Mastrigt (2015) subjects stated discomfort in the neck when watching IFE. In a context mapping study by van Rosmalen et al. (2010), participants requested a headrest for head support. The question is if head/neck support for watching IFE in a reclined posture will lower muscle activity and offer the passenger more comfort.

Figure 2. Subject watching IFE in slouched posture while flexing head forward with respect to the trunk (from Smulders et al. (2016))

1.2. Theoretical biomechanical analysis

Neck flexion theoretically stretches and contracts the neck muscles. In a simulation with the AnyBody™ model, it was found that the neck force increases in the musculus trapezius pars descendens (TRP-UP) and transverse (TRP-MID) due to stretching of the muscle, when the head keeps a horizontal view and the backrest reclines backwards.

To compensate for the force exerted by the trapezius muscle the sternocleidomastoideus (SCM) should theoretically be active if there is no headrest. The hypothesis is therefore that a headrest, which supports the head/neck while sitting in this slouched posture, will not change or lower neck muscle activity (e.g. SCM) and will benefit the comfort experience of the user.

2 Materials and methods

To study the effect of the headrest in a slouched position, EMG, posture and expected long-term comfort were recorded of 21 subjects sitting in a lounge seat with a backrest angle of 40 degrees. 12 subjects started with the condition with headrest and the other 9 without headrest. Surface RA-EMG was recorded of the TRP-UP and SCM for 5 minutes in each condition. Postures were recorded by camera in the different conditions. Expected long-term comfort was recorded by questionnaire.

2.1. Subjects

11 female and 10 male American, Chinese, Dutch and Iranian adults with no neck injuries and/or complaints in the past six months and who have flown in the past, participated in this study (Table 3). Subjects were asked to wear top clothing without a collar – preferably a T-shirt – for easy sensor placement.

Table 2. Anthropometrics of subjects

		Mean	*SD*
Male (n=10)	*Age [Years]*	31,9	6,4
	Stature [m]	1,81	0,04
	Weight [Kg]	87,2	21,6
Female (n=11)	*Age [Years]*	24,4	1,0
	Stature [m]	1,72	0,08
	Weight [Kg]	64,9	8,7

2.2. Experimental setup and stimuli

The study took place at two different locations with the same setup. Seven subjects were tested at the Human Factors and Ergonomics lab of Zodiac Seats US in the USA and fourteen at the ID-User Labs of the Delft University of Technology in the Netherlands.

Surface electromyography was used to measure muscle tension in the m. sternocleidomastoid (SCM) and m. trapezius upper fibers (TRP-UP) in three conditions: lying flat (condition A), sitting slouched watching with (condition B) and without (condition C) a headrest.

To stimulate full muscle relaxation in condition A (which functions as a benchmark of full relaxation), subjects lied down on a mattress with a pillow. To stimulate a TV/IFE watching posture, subjects sat slouched in an IKEA® POÄNG lounge seat with a 40° reclined backrest and leg support, facing a 15" LCD monitor (further named IFE screen) featuring a TED talk on the subjects' interests at 1,69m distance with its centre at each participant's eye height (as recommended by Yoichi et al. (2012)). In condition B the seat had a headrest, in condition C the headrest was removed (see Figure 3). It is important that subjects rest their arms on their lap in condition B and C, to limit influence of its 10% of the total body weight load (Roebuck, Kroemer, & Thomson, 1975; Snijders, Nordin, & Frankel, 1995) on muscle activity in the shoulder-neck region. The use of the fixed armrest would result in measuring different loads due to anthropometric differences among subjects.

After each condition subjects were asked to file a questionnaire on their expected long-term comfort in general (all-over experience), for the neck, head and eyes. For each body part a score needed to be given by drawing a vertical line on a horizontal score-line with 'not comfortable' and 'very comfortable' at its ends. For each given score, subjects were asked to substantiate in writing.

Figure 3. Left: condition B - subject sitting in the seat with headrest
Right: condition C - subject sitting in the seat without headrest

To put measured muscle tension into perspective, subjects conducted a maximal voluntary contraction (MVC) of the neck muscles by flexing the head against a load created by a TheraBand™ Red (medium strength) or Green (heavy strength; for some strong subjects), and extending the head against the headrest by the end of the study.

2.2.1. EMG sensor positions

The two electrodes were applied parallel to the muscle fiber direction on the dominant middle portion of the muscle belly (Delsys, 2012; Konrad, 2005). Muscle belly positions were palpated and the sensor for the TRP-UP was placed at C5/C6 level, ±2 cm lateral to midline (Sommerich, Joines, Hermans, & Moon, 2000) and the sensor for the SCM was placed on the lower 1/3rd between the sternal notch and mastoid process (Falla, Dall'Alba, Rainoldi, Merletti, & Jull, 2002). Since the head was kept parallel to the lateral plane, only muscle activity at one side was measured.

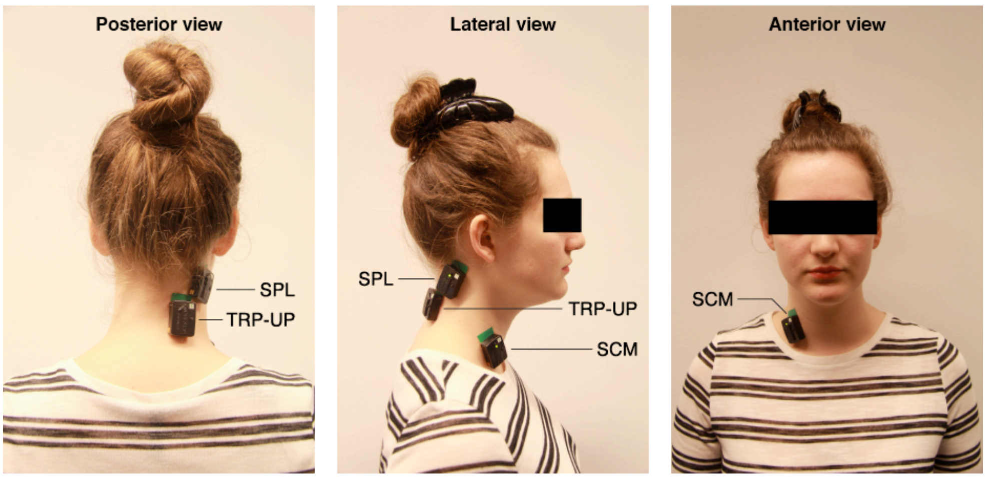


Figure 4. Posterior, lateral and anterior view of sensor placement on the splenius and semispinalis area (SPL), the upper trapezius fibers (TRP-UP) and the sternocleidomastoid (SCM)

2.3. Apparatus

In both the USA and The Netherlands locations the exact same Delsys® Trigno™ Wireless EMG System (2000 Hz sampling rate) and a laptop with Delsys® EMGworks™ were used to measure muscle activity of the neck muscles. A Mitutoyo® digital protractor angle gage and an iPhone 5 gyro were used to set the seat backrest to an angle of approximately 40˚. In the USA study an electric weight scale and a Seca® 700 analogue stadiometer were used to determine subjects weight and height. In The Netherlands an electric weight scale and a GPM antropometer were used. In the USA a Canon® 6D DSLR camera with a Canon® EF 24-105mm f/4.0L IS USM (set to 24mm) at a fixed position (1,38m 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 17-55mm f/2.8 IS USM (set to 17mm) was used.

2.4. Procedure

Subject briefing and preparation

Subjects were first briefed on the procedure of the study and were requested to sign a consent and NDA form, state their date of birth and nationality. Subjects were then requested to take off their shoes to measure their weight and length. Next, subjects were asked to take a seat in preparation of sensor placement.

Skin preparation and sensor placement

Areas for sensor placement on the subject's skin were cleaned by removing dead skin cells and other skin surface 'pollution' by sticking and pealing 3M Transpore™ surgical tape multiple times on the skin and then softly rubbing alcohol wipes on the skin (Delsys, 2012; Hermens, Freriks, Disselhorst-Klug, & Rau, 2000; Konrad, 2005; Letizi, 2016). Sensors were placed on the subject's lateral right as described in §2.2.2.

Signal validity check

The validity of the EMG signal were checked by inspecting the baseline noise ratio, baseline offset and baseline shift (Konrad, 2005; Letizi, 2016). The raw EMG signal of the SCM was inspected by letting subjects flex their head forward to the opposite side (Soderberg, 1992). The same was done for the TRP-UP by having subjects raise their shoulders (Soderberg, 1992).

Condition A: lying on the ground

Subjects were asked to lie flat on a mattress with pillow and fully relax for 5 minutes first (see Figure 3). During this period the room was darkened to help subjects to fully relax. This measurement functions as the benchmark for full muscle relaxation. Thereafter the subjects were asked to stand up and to state their expected long-term comfort by questionnaire.

Preparing sitting position

Subjects 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. For posture analysis, a lateral picture was taken of the subject's sagittal plane in the seat. The height of the IFE screen was adjusted to meet the subject's eye height with the IFE screen's centre (Yoichi et al., 2012). Thereafter the subjects were asked to stand up and select a TED talk movie on their interests.

Condition B and C

To prevent order effects, (approximately) half of the subjects started sitting in condition B and the other half of the subjects started in condition C.

Condition B: sitting slouched with headrest

Subject's 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 looking at the IFE screen to watch a movie for 5 minutes (see Figure 3). During this activity, EMG signals were continuously recorded for 5 minutes. Thereafter a lateral picture of the posture was taken and the movie paused. The subject was asked to fill in the expected long-term comfort questionnaire. Thereafter the subjects were asked to stand up and take a break for 2 minutes, to minimize fatigue (C. F. Tan, Chen, & Rauterberg, 2010).

Condition C: sitting slouched without headrest

The headrest of the seat was removed. Subject's were asked to sit in a slouched posture (back against reclined backrest), rest the arms in their lap and looking at the IFE screen to watch a movie for 5 minutes, but without resting the head against the seat (see Figure 3). The same procedure as in *condition B* was followed.

Maximal Voluntarily Contraction

Lastly the subject was asked to conduct maximal voluntarily contraction (MVC) of the flexion and extension neck muscles. This was executed at the end of the study, since MVC has some discomfort effects due to extensive contractions of the muscles, which need some recovery afterwards.

Subjects were asked to push their head against the TheraBand™ (flexion) – which was connected to the seat frame – as hard as they can for 3 seconds. They were verbal encourage when needed. Thereafter they had a recovery break of 30 seconds and repeated the exercise another two times. Delsys EMGworks® automatically determined the highest MVC of the three contractions. A similar procedure was followed to determine MVC for extension by placing the headrest back on the seat and ask subjects to push their head against the headrest (extension) as hard as they could for 3 seconds. This too was repeated another two times and the highest MVC was determined.

2.5. Measures

Muscle activity

Two subjects had to be excluded from the EMG study due to a software crash that resulted in lost data. Collected EMG data of the TRP-Up and SCM in conditions A, B and C and of the flexion and extension MVC's of each subject were processed with Delsys® EMGworks™ . First the baseline offset was removed and the root-mean-square (RMS) was taken of the raw signal. Then the microvolt 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); MVC extension for the TRP-UP and MVC flexion for the SCM. Expressing the signal in %MVC makes comparison between subjects possible, since EMG data is of a subject dependent nature. Of each data set an as large as possible sample without noise was taken to calculate a mean muscle activity of the TRP-UP and SCM in each condition, expressed in %MVC. In Microsoft Excel a paired t-test was taken to check for significant differences between the conditions ($p < 0.05$), as well for influence of testing order, gender and testing location.

Expected long-term comfort

One subject had to be excluded due to not filing one of the questionnaires. All rates were collected by measuring the given scores on the 10 cm long score-line with a ruler and all handwritten comments were typed down and were processed with Microsoft Excel. Since comfort values are not normally distributed, the Wilcoxon test was used in addition to a *t* test, to look for differences between conditions B and C. The significance between the scores for conditions B and C was calculated ($p < 0.05$) per rated area. In addition, influence of testing order, gender and testing location were tested on significance.

Head-neck posture

Two subjects had to be excluded from the study; one due to missing pictures of one condition, the other due to deformation of the seat by subject'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, C7, tragus, canthus and visual target (the centre of the IFE screen), and then lines were drawn between those points (see Figure 5). Of each line the angle was recorded based on Psihogios, Sommerich, Mirka, and Moon (2001) and processed in Microsoft Excel. A paired t-test was taken of each angle to check for significant differences between the conditions ($p < 0.05$), as well for influence of testing order, gender and testing location.

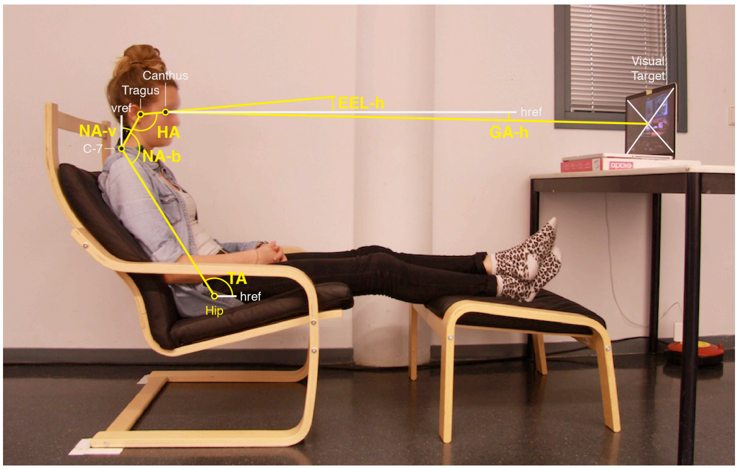


Figure 5. Lateral analysis of posture in Adobe Illustrator.
Angles describing the head-neck posture (based on Psihogios et al. (2001))

3 Results

The recorded mean muscle activity for conditions A, B and C, expressed as a percentage of the MVC, can be found in Figure 6. The EMG data shows no significant difference in both the TRP-UP as the SCM between condition B and C (see Table 3). However, the SCM significantly relaxed in condition B over A, however only with 0,5%MVC on average.

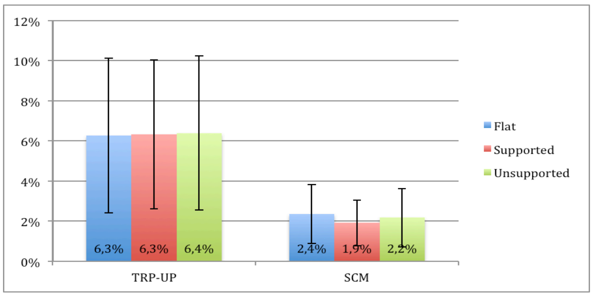


Figure 6. Mean muscle activity as a percentage of MVC (n=19)

Table 3. T-test of muscle activity as a percentage of MVC (n=19)

Condition	*SCM*	*TRP-UP*
AB	0,003 *	0,4
AC	0,2	0,2
BC	0,05	0,3

Expected long-term comfort scores for *general* (all-over) *comfort*, *neck comfort*, *head comfort* and *eye comfort* can be found in Figure 7. Subjects rated expected long-term comfort in *general*, in the *neck* and the *head* significantly higher in the condition with a headrest (condition B). There was no significant difference rated at the eyes. No significant influence of testing order on the comfort scores was found, except for *eye comfort* in condition B (p≈0,41).

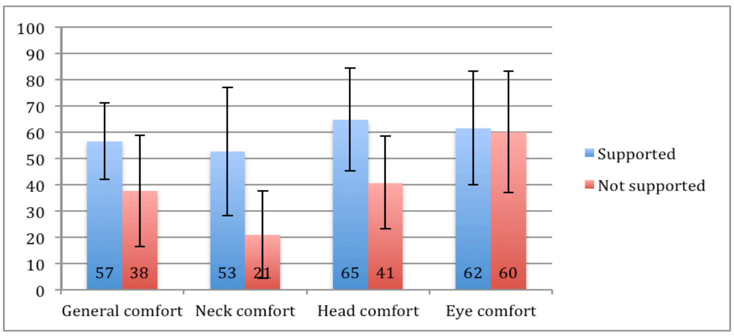


Figure 7. Mean comfort scores with SD (n=20)

The inclinations describing the head-neck posture in conditions B and C can be found in Table 4. The inclination data shows the posture was significantly different between condition B and C, except for HA (p≈0,13). Without head support (B) the head was found to be more upright in respect of without head support (C).

Table 4. Posture inclinations (for angle description, see Figure 5)

Angle	*TA*		*NA-b*		*NA-v*		*HA*		*EEL-h*		*GA-h*	
Condition	B	C	B	C	B	C	B	C	B	C	B	C
Mean	126,3°	124,4°	126,5°	117,4°	17,3°	28,2°	130,9°	132,0°	23,6°	13,8°	-2,6°	-2,2°
SD	2,1°	2,6°	4,7°	5,1°	5,0°	4,6°	6,0°	6,4°	5,6°	5,3°	1,0°	1,2°
Max	132,0°	131,4°	136,4°	128,0°	24,7°	35,7°	144,3°	142,8°	36,2°	27,6°	-0,9°	0,6°
Min	123,6°	120,6°	118,6°	108,1°	8,1°	18,7°	120,2°	121,5°	14,7°	5,2°	-5,5°	-5,0°
Difference (mean)	1,83°		9,11°		10,94°		1,09°		9,85°		-0,41°	
Wilcoxon	0,00026 *		0,00008 *		0,00008 *		0.12602		0,00012 *		0,00578 *	

4 Discussion

It appeared that there were no significant differences in EMG between both conditions B and C. Expected long-term comfort was rated highest in the condition with a headrest (B), indicating there may be a psychological effect by perceiving support and body contact, positively influencing perceived comfort. Franz, Durt, Zenk, and Desmet (2012) describe a similar effect on contact, were neck support benefitted the perceived comfort.

The expectation of having more comfort in the long term may actually positively influence the all over experienced comfort of a passenger during a flight, a phenomena described by Naddeo, Cappetti, Califano, and Vallone (2015) in the context of a bed. It is therefore recommended to further investigate the impact of head support on perceived comfort and discomfort. Additional simulations with AnyBody™ on e.g. the m. sternocleidomastoideus, m. splenius capitis and m. semispinalis would be preferable. Also the duration of EMG measurement in this study was limited. 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 muscle activity and fatigue and the passenger comfort and discomfort over time.

The posture between conditions B and C was significantly different. Without head support by a headrest the head was found to be more upright and placed above the rotation axes of the neck. The fact that no difference was found in EMG indicates that humans tend to look for a head position that is neutral. Neutral in the sense that the least energy is needed to keep the head upright. Regarding the seat experience, stability by head support is preferred. These data indicate that it is important for seats to facilitate a neutral position for the head and in a reclined seat head support may have a positive psychological effect on the user.

5 Conclusion

Head support for watching IFE in a slouched posture has no significant effect on muscle activity, since subjects will adapt their posture to have minimal muscle activity by placing the head above the rotation axes when support is lacking. However psychologically, head support will benefit the expected long-term comfort experience of the user.

Acknowledgments We want to thank J.M.A. Bouwens, S. Akkerman and D.M. Lips for their contribution, and a special thanks to S. Snider and B.J. Naagen for their great help and support in setting up this study. We also want to thank Prof. Nicola Cappetti for conducting AnyBody™ simulations for us. Prof.dr.ir. R.H.M. Goossens for sharing his knowledge on biomechanics. Zodiac Seats US for lending the EMG equipment and Delsys® for training and support. And lastly all the subjects who took part in this study.

References

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.

Chaffin, D. B. (1973). Localized muscle fatigue-definition and measurement. *Journal of Occupational and Environmental Medicine, 15*(4), 346-354.

Dalassio, D. J. (1980). *Wolff's Headache and Other Head Pain*. Oxford: Oxford University Press.

Delsys. (2012). Trigno Wireless System User's Guide. Retrieved from delsys.com/Attachments_pdf/Trigno%20Wireless%20System%20Users%20Guide%20(MAN-012-2-3).pdf

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.

Franz, M., Durt, A., Zenk, R., & Desmet, P. M. (2012). Comfort effects of a new car headrest with neck support. *Appl Ergon, 43*(2), 336-343. doi:10.1016/j.apergo.2011.06.009

Goossens, R. H. M., Snijders, C. J., Roelofs, G. Y., & Buchem, F. V. (2003). Free shoulder space requirements in the design of high backrests. *Ergonomics, 46*(5), 518-530.

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.

Hiemstra-van Mastrigt, S. (2015). *Comfortable passenger seats: Recommendations for design and research*. Delft: Delft University of Technology.

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.

Kilincsoy, Ü., Wagner, A., Bengler, C., Bubb, H., & Vink, P. (2014). *Comfortable rear seat postures preferred by car passengers*. Paper presented at the 5 th International Conference on Applied Human Factors and Ergonomics.

Konrad, P. (2005). The abc of emg. *A practical introduction to kinesiological electromyography, 1*, 30-35.

Kroemer, K. H. E., & Hill, S. G. (1986). Preferred line of sight angle. *Ergonomics, 29*(9), 1129-1134.

Letizi, J. (2016). [Personal communication, Delsys EMG training].

Meziat Filho, N., Coutinho, E. S., & e Silva, G. A. (2015). Association between home posture habits and low back pain in high school adolescents. *European Spine Journal, 24*(3), 425-433.

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.

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.

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.

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.

Roebuck, J. A., Kroemer, K. H. E., & Thomson, W. G. (1975). *Engineering anthropometry methods* (Vol. 3): Wiley-Interscience New York.

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.

Snijders, C. J., Nordin, M., & Frankel, V. H. (1995). *Biomechanica van het spier-skeletstelsel; grondslagen en toepassingen. Lemma, Utrecht*. Retrieved from

Soderberg, G. L. (1992). Recording techniques. *Selected topics in surface electromyography for use in the occupational setting: Expert perspectives*, 31-35.

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.

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.

Tan, C. S. S., Van den Bergh, J., Schöning, J., & Luyten, K. (2014). Towards Empathic TV Interaction using Body Postures.

Travell, J. (1967). Mechanical headache. *Headache: The Journal of Head and Face Pain, 7*(1), 23-29.

Travell, J. G., & Simons, D. G. (1992). *Myofascial pain and dysfunction: the trigger point manual* (Vol. 2): Lippincott Williams & Wilkins.

van Rosmalen, D. M. K., Groenesteijn, L., Boess, S. U., & 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.

van Rosmalen, D. M. K., Groenesteijn, L., Boess, S. U., & Vink, P. (2010). Eisen aan een loungestoel om naar een scherm te kijken. *Tijdschrift voor ergonomie, 2, 35, 4-10*.

van Veen, S. A., 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. (2016). *Vehicle seat comfort and design*: TU Delft Library.

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.

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

Appendix C Applied Ergonomics paper: Neck posture and muscle activity in a reclined business class aircraft seat watching IFE with and without head support

At the time of publishing this graduation thesis, this study was selected by the ICC technical committee and submitted at Applied Ergonomics of Elsevier. Changes in the final publication may apply.

Neck posture and muscle activity in a reclined business class aircraft seat watching IFE with and without head support

M. Smulders[ab*], A. Naddeo[c] , N. Cappetti[c], E.D. van Grondelle[a] , U. Schultheis[b1] and P. Vink[a]

[a] Faculty of Industrial Design Engineering, Delft University of Technology,
Landbergstraat 15, 2628CE Delft, The Netherlands

[b] Human Factors and Ergonomics, Zodiac Seats U.S. LLC,
2000 Weber Drive, Gainesville, Texas 76240, United States of America

[c] Department of Industrial Engineering, University of Salerno,
Via Ponte don Melillo, 1, 84084 Fisciano, Salerno, Italy

* Corresponding author. E-mail address: info@maximsmulders.com

[1] Present address: General Motors LLC
29427 Louis Chevrolet Rd., Warren, Michigan 48093, United States of America

Abstract

The purpose of this study is to research 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. Subjects indicated they expect to experience more comfort with a headrest when watching IFE for 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 necessary 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.

Keywords: EMG, posture, neck angle, aircraft seat, headrest, comfort

Abbreviations:

EMG	Electromyography: an electrodiagnostic medicine technique for evaluating and recording the electrical activity produced by skeletal muscles.
IFE	In Flight Entertainment: the screens on board of an aircraft to entertain passengers, featuring (depending on what the airline offers) movies, (live) TV, games, interactive maps, magazines, et cetera. 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.
MVC	Maximum Voluntary Contraction: maximum force, which a human subject 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.
VDU	Visual Display Unit, a device for displaying input signals as characters on a screen.

1. Introduction

This paper 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.

Such an insight could lead to a new design requirement and/or recommendation for headrest 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 an important decisive factor for passengers when they book 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, Hiemstra-van Mastrigt, Kamp, and Vink (2014) discuss neutral head angles in the context of tablet use. Recommendations on head angles when using VDU's 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.

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

It is important to determine the posture taken in a seat for the activity of watching IFE in the aircraft, since the head inclination is influenced by the inclination of the trunk (Delleman et al., 2004). The taken posture also influences comfort (Naddeo, Cappetti, & D'Oria, 2015; van Veen et al., 2014) and facilitating a good posture may – on the long run – prevent musculoskeletal injuries (Delleman et al., 2004).

As observed in studies by Knijnenburg (2005), van Rosmalen, Groenesteijn, Boess, and Vink (2009, 2010), Filho, Coutinho, and 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 *in flight entertainment* (IFE) during flight (see Table 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 1 and Table 2 for a comparison.

A possible explanation for this preference for a reclined/slouched posture may be the lower back muscle activity, as shown in the study by Goossens, Snijders, Roelofs, and Buchem (2003). A study based on an experiment with one subject of Wilke, Neef, Caimi, Hoogland, and Claes (1999) and a study based on five subjects of Rohlmann, Zander, Graichen, Dreischarf, and Bergmann (2011) may give an indication that a slouched posture also lowers pressure on 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, 1987) show that neck muscle activity was reduced when neck flexion was increased by a backward inclination of the trunk (thoraco-lumbar spine).

Table 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	20	Observation / Interview	A slouched posture was taken by subjects as most comfortable for watching TV.
Van Rosmalen et al. (2009, 2010)	Watching TV at home in a lounge seat	13	Observation / Questionnaire / Context mapping	Subjects 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.
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 subjects 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 subjects as most comfortable for watching IFE. Half the subjects rested the head against the backrest and conducted deorsumversion of the eyes (looking 'downward'), where the other half flexed the head forward to watch the IFE screen.

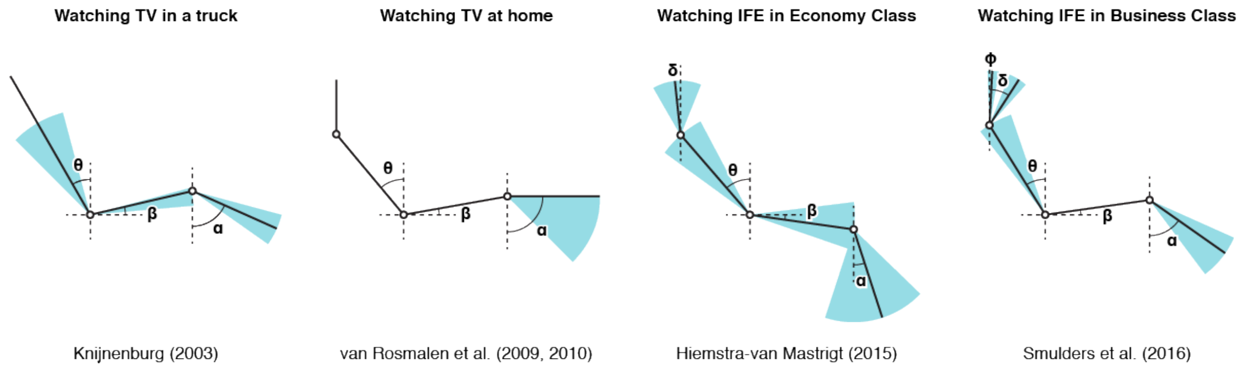


Figure 1 2D visual representation of seat angles as given in Table 3. Black lines represent mean values, where the blue areas represent the observed range (minimal and maximal angles, without outliers) (figure representation based on Hiemstra-van Mastrigt (2015)).

Table 2 Seat/body angle comparison. See Figure 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]	Not investigated, but was set parallel to backrest
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°) [2]	-8° (SD=6.6°) [2]	41° (SD=6.1°) [2]	-6° (SD=13°) [2]
Smulders et al. (2016)	Watching IFE in a business class seat	10	55° (SD=11.6°)	Not investigated, but was set at 5°	32° (SD=5.6°)	38° (SD=9°) /12° (SD=7°) [3]

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

[2] Data were acquired by secondary analysis of the study data of Hiemstra-van Mastrigt (2015)

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

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 more scarce – an IFE screen should be below eye level and oriented perpendicular to the line of sight (see Figure 2). Psihogios 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 results in other preferred posture, head, neck and eye angles. 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 2). Also Kroemer and Hill (1986) and Mon-Williams, Burgess-Limerick, Plooy, and Wann (1999) show a more horizontal view is preferred when reclining the backrest and increasing the eye-screen distance.

When reclining the backrest (30-41˚) in a business class seat while watching IFE, people tend to or 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 3), which was observed in the study by Smulders et al. (2016) (see also Table 2).

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 30˚, which according to Chaffin (1973) 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; J. Travell, 1967; J. G. Travell & Simons, 1992). It can be presumed that passengers are trying to look for support when flexing the head forward (see C in Figure 3) by using a pillow (which is commonly supplied to passengers on long haul business class flights).

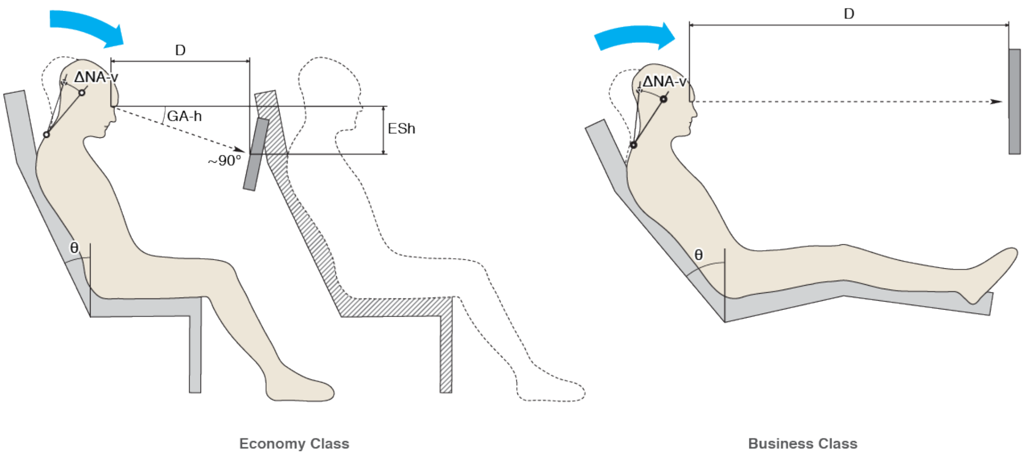


Figure 2 Economy class and business class screen orientation (anatomical representation indicative only).

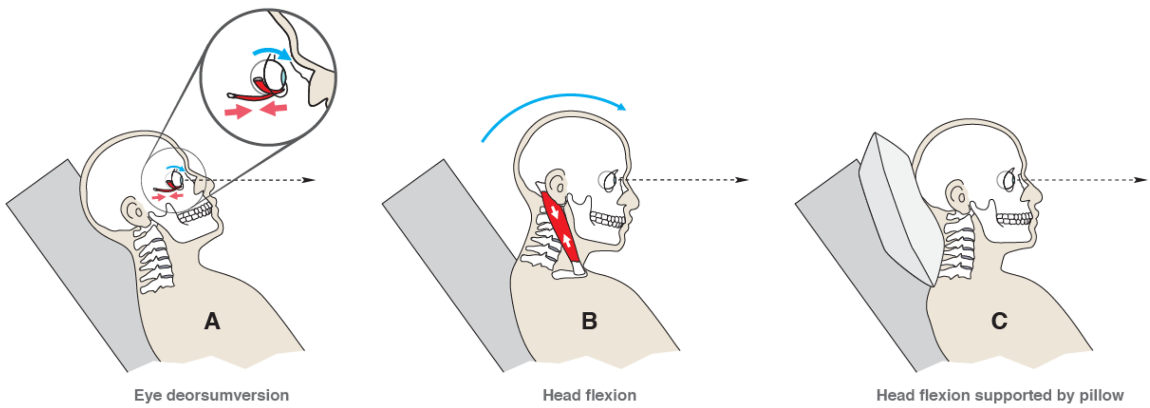


Figure 3 Subject watching IFE in slouched posture while A) deorsumducting the eyes by contracting a.o. the m. inferior rectus and m. inferior oblique B) flexing the head forward with respect to the trunk by contracting a.o. the m. sternocleidomastoid and C) flexing the head forward while gaining support of a pillow (anatomical representations indicative only).

In the studies of van Rosmalen et al. (2009) and Smulders et al. (2016) it was observed that subjects lacked neck/head support when watching TV/IFE in the slouched posture. In the study performed by Hiemstra-van Mastrigt (2015) subjects 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, subjects 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 (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 could increase the activity of the flexion muscles to maintain (static) position. The question is whether this is the case. This could be answered by using a biomechanical model and *electromyography* (EMG).

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 4), it was found that neck muscle activity decreases (see Figure 5) when the head flexes to gain 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 Figure 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 clavicular (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 lateral rotation axis in the neck.

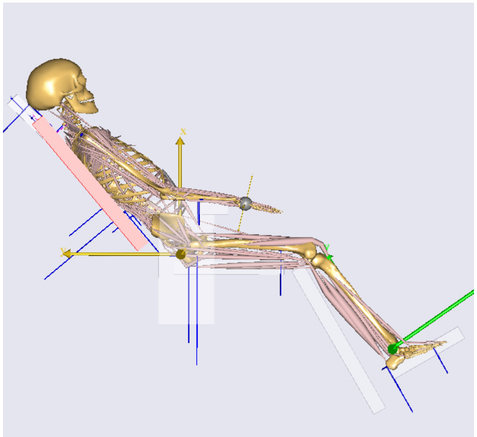


Figure 4 Musculoskeletal model with supported back, buttocks, upper legs and lower arms (AnyBody Technology A/S, Aalborg, Denmark).

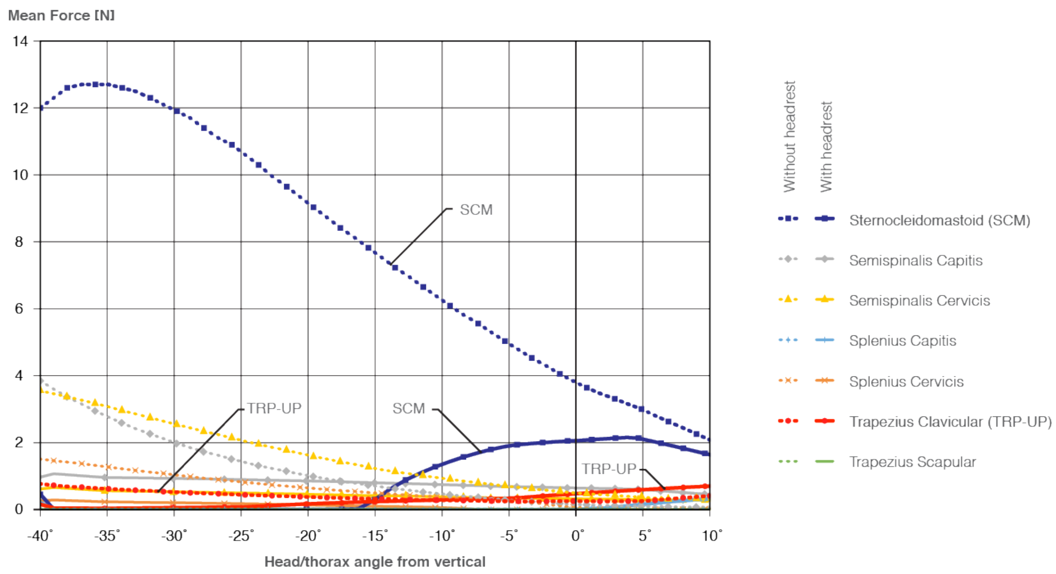


Figure 5 AnyBody™ simulation of mean muscle forces [N] when head flexes from parallel to backrest (set at -40°) to upright (0˚) and beyond (till 10˚).

2. Materials and methods

To study the effect of the headrest in a slouched position, *surface electromyography* (sEMG), posture and (subjective) *expected long-term comfort* ratings were recorded of 21 subjects sitting in a lounge seat with a backrest recline of 40˚, simulating an aircraft business class seat. 12 subjects started in the condition with headrest and the other 9 without headrest. Surface EMG was recorded of the m. trapezius pars descendens (TRP-UP) and m. sternocleidomastoid (SCM) for 5 minutes in each condition. Postures in the different conditions were recorded by camera. *Expected long-term comfort* ratings were recorded through a questionnaire.

2.1. Subjects

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 3). Subjects were asked to wear top clothing without a collar – preferably a T-shirt – for easy sensor placement.

Table 3 Characteristics of subjects

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

2.2. Experimental setup and stimuli

The study took place at two different locations with the exact same setup and EMG equipment. Seven subjects were tested at the Human Factors and Ergonomics lab of Zodiac Seats US 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: lying flat (condition A), sitting slouched watching IFE with a headrest (condition B) and without a headrest (condition C).

To stimulate full muscle relaxation in condition A (which functions as a benchmark of full relaxation), subjects lay down on a mattress with a pillow (see Figure 6) in a dark room.

Figure 6 Mattress with pillow for full relaxation measurement.

To stimulate a TV/IFE watching posture for conditions B and C, subjects sat slouched in an IKEA® POÄNG lounge seat with a ±40˚ reclined backrest and leg support, facing a 15" LCD monitor (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 subjects' interest (www.ted.com/topics). The IFE screen was placed at a 1.69m distance and the screen height was set at each subject's eye height (as recommended by Yoichi et al. (2012)). In condition B the seat had a headrest (see Figure 7), in condition C the headrest was removed (see Figure 8). It is important that subjects 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.

After each condition subjects 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 hours (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 score-line with 'not comfortable' and 'very comfortable' at its ends. For each given score, subjects were asked to elaborate in writing.

To put measured muscle tension (sEMG) into perspective, subjects 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 some physically stronger subjects), and extending the head against the headrest (exercise inspired by Murray, Lange, Nørnberg, Søgaard, and Sjøgaard (2015)).

Figure 7 Condition B: subject sitting in the seat with headrest.

Figure 8 Condition C: subject sitting in the seat without headrest.

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.

With *surface EMG* (sEMG) only superficial muscles with their belly located directly beneath the skin surface can be measured (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, Feeback, & Dudley, 1995) – has some tissue directly under the skin, but 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 results in measuring crosstalk of the TRP and SCM (Mayoux Benhamou, Revel, & Vallee, 1995). Although Sommerich et al. (2000) cites multiple studies which measured the splenius with sEMG, Mayoux Benhamou et al. (1995) argues it can only be measured by fine-wire or needle electrodes. It was therefore decided to exclude the SPL from this study.

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, 2012; Konrad, 2005). Muscle belly positions were palpated 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); 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); Zipp (1982)), as shown in Figure 9. Since the head was kept parallel to the lateral plane, only muscle activity at one side (right side) was measured.

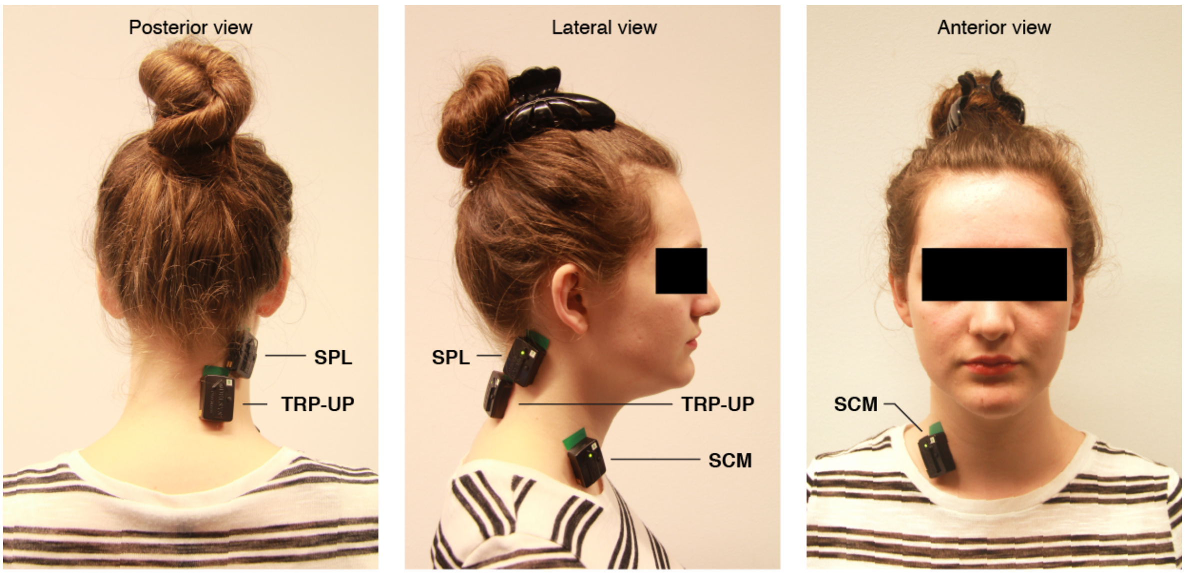


Figure 9 Posterior, lateral and anterior view of sensor placement on the splenius and semispinalis area (SPL) (excluded from study, as described in §2.2.1), the trapezius pars descendens (TRP-UP) and the sternocleidomastoid (SCM).

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 gage was used to set the seat backrest to an angle of approximately 40˚. In the USA a Canon® 6D DSLR camera with a Canon® EF 24-105mm f/4.0L IS USM (set to 24mm) at a fixed position (1,38m 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 17-55mm f/2.8 IS USM (set to 17mm) was used. All instrumentation used was set to SI units.

2.4. Procedure

Subject briefing and preparation

Subjects 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. Subjects were then requested to take off their shoes (shoes were off for the duration of the study) to measure their weight and length. Next, subjects were asked to take a seat in preparation of sensor placement.

Skin preparation and sensor placement

Areas for sensor placement on the subject'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, 2012; Hermens, Freriks, Disselhorst-Klug, & Rau, 2000; Konrad, 2005; Letizi, 2016). Sensors were placed on the subject's lateral right as described in §2.2.2.

Signal validity check

The validity of the EMG signal were checked by inspecting the baseline noise ratio, baseline offset and baseline shift (Konrad, 2005; Letizi, 2016). The raw EMG signal of the SCM was inspected by letting subjects flex their head forward to the opposite side (Soderberg, 1992). The same was done for the TRP-UP by having subjects raise their shoulders (Soderberg, 1992).

Condition A: lying flat

Subjects were asked to lie flat on a mattress with pillow and fully relax for 5 minutes first (see Figure 6). During this period the room was darkened to help subjects to fully relax. This measurement functioned as the benchmark for full muscle relaxation. Thereafter subjects were asked to stand up and to state their *expected long-term comfort* on the questionnaire.

Preparing sitting position

Subjects 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. For posture analysis, a lateral picture was taken. The height of the IFE screen was adjusted to meet the subject's eye height with the IFE screen's centre (Yoichi et al., 2012). Thereafter the subjects were asked to stand up and select a TED talk movie on their interests.

Order effect prevention

To prevent order effects, (approximately) half of the subjects started sitting in condition B and the other half of the subjects started in condition C.

Condition B: sitting slouched with headrest

Subjects 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 7) while EMG signals were continuously recorded for 5 minutes during this activity. At the end a lateral picture of the posture was taken and then the TED-talk movie paused. The subject was asked to fill in the *expected long-term comfort* questionnaire. Thereafter the subjects were asked to stand up and take a break for 2 minutes, to minimize fatigue (Tan, Chen, & Rauterberg, 2010).

Condition C: sitting slouched without headrest

The headrest of the seat was removed and subjects were asked to watch a TED-talk movie for 5 minutes, but without resting the head against the seat (see Figure 8). The same procedure as in *condition B* was followed.

Maximal Voluntary Contraction

Lastly subjects 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.

Subjects were asked to push their head against a TheraBand® (flexion) – which was connected to the seat frame – as hard as they could for 3 seconds (see Figure 10). They were verbally encouraged when needed. Thereafter subjects 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 subjects to push their head against the headrest (extension) as hard as they could for 3 seconds (see Figure 11). This procedure was repeated another two times and the highest MVC-EMG was determined.

Figure 10 MVC flexion by pushing against an elastic TheraBand®

Figure 11 MVC extension by pushing against the headres

2.5. Measures

Analysis of EMG

Two subjects 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 min) 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 Microsoft® Excel™ a paired t-test was taken of the mean %MVC signals to check for significant differences ($p < 0.05$) between the conditions, as well for influence of testing order, gender and testing location.

Analysis of expected long-term comfort rating

One subject had to be excluded due to not completing all questionnaires. All ratings were collected by measuring the given scores on the 10 cm long scoreline with a ruler and all handwritten comments were typed down and processed with Microsoft® Excel™. 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 ($p < 0.05$) per rated body area (eyes, neck, head) and whole body. In addition, any influence of testing order, gender and testing location were tested with a paired t-test ($p<0.05$).

Analysis of head-neck posture (2D)

Two subjects had to be excluded from the study; one due to missing pictures of one condition, the other due to deformation of the seat by subject'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 12). The angle of each line was recorded (based on Psihogios et al. (2001)) and processed in Microsoft® Excel™. A paired t-test was taken of each angle to check for significant differences between the conditions ($p < 0.05$), as well as for any influence of testing order, gender and testing location.

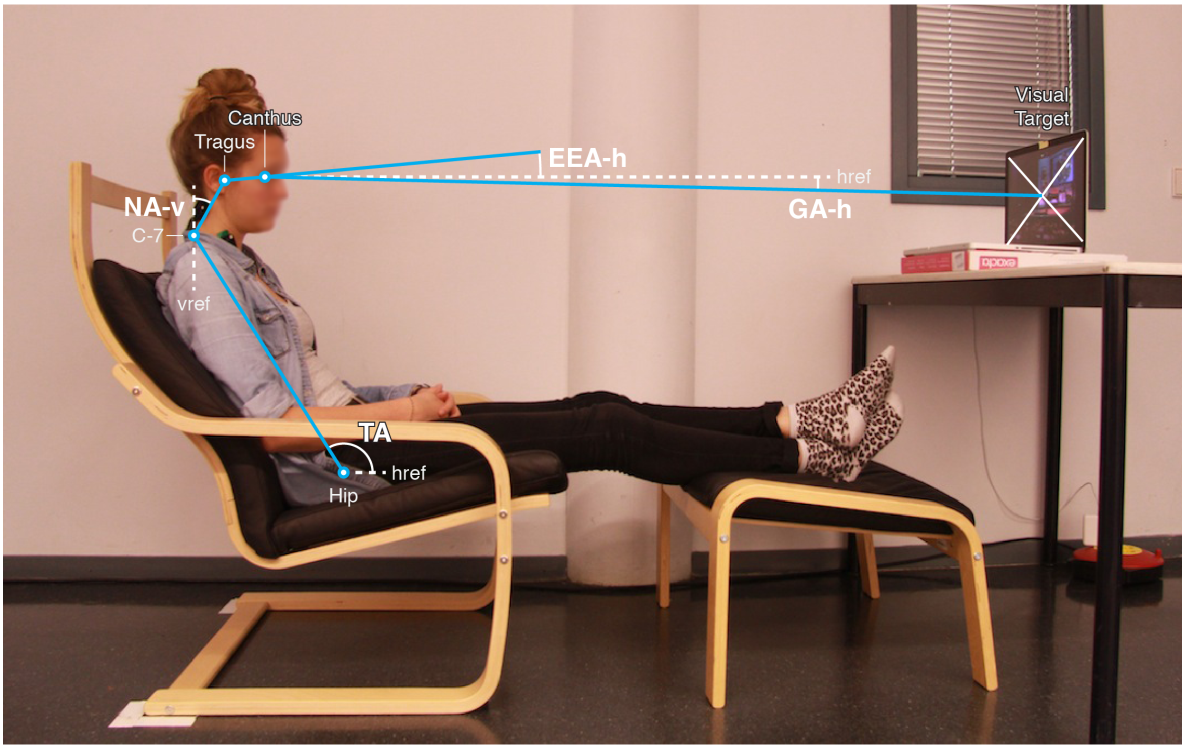


Figure 12 Lateral analysis of posture, where the following angles describe the head-neck posture: TA: Trunk Angle (through hip-joint and C7) relative to horizontal, NA-v: Neck Angle (through C7 and Tragus) relative to vertical, EEA-h: Eye-Ear Angle (through Tragus and Canthus) relative to horizontal, GA-h: Gaze Angle (through Canthus and centre of the visual target) relative to horizontal. Angle representation based on Psihogios et al. (2001).

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 13. The EMG data show no significant difference in both the TRP-UP as the SCM between condition B and C (see Table 4). However, the SCM showed a low activity level (2%MVC on average).

Table 4 T-test of muscle activity as a percentage of MVC (n=19)

Condition	*SCM*	*TRP-UP*
AB	0.003 *	0.4
AC	0.2	0.2
BC	0.05	0.3

Expected long-term comfort scores for *whole-body comfort*, *neck comfort*, *head comfort* and *eye comfort* are shown in Figure 14. *Whole body*, *head* and *neck comfort* was significantly higher in the condition with a headrest (condition B). There was no significant difference found for the eyes. No significant influence of testing order on the comfort scores was found, except for *eye comfort* in condition B ($p \approx 0.41$).

The inclinations describing the head-neck posture in conditions B and C can be found in Table 5 and are visualised in Figure 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 in respect to with head support (B).

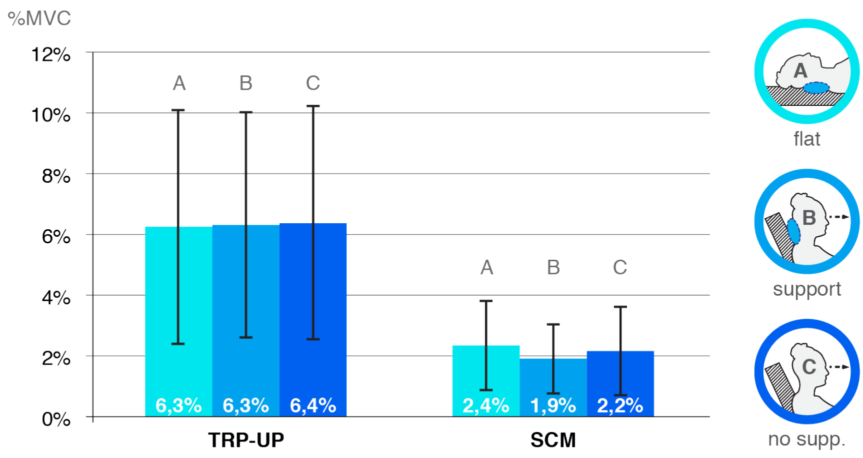


Figure 13 Mean muscle activity as a percentage of MVC (n=19)

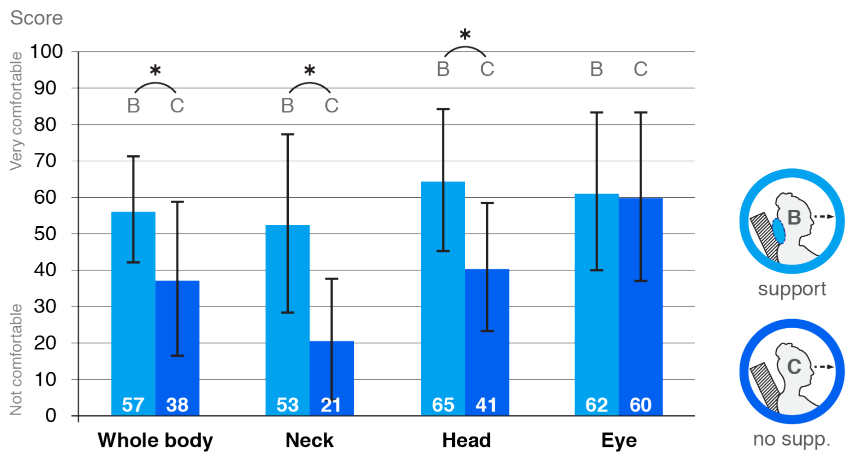


Figure 14 Mean comfort scores with SD (n=20)

Table 5. 2D posture inclinations. See Figure 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	0.00018 *		0.00014 *		0.00012 *		0.00578 *	

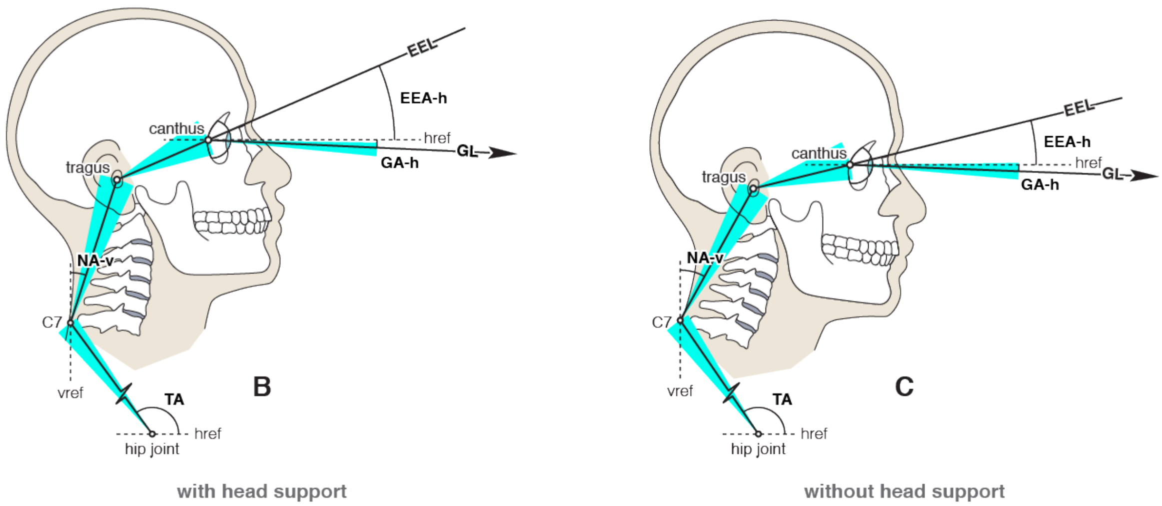


Figure 15 2D posture angles (anatomical representation indicative only).
Left: condition B, with head support. Right: condition C, without head support. Black lines represent mean values, where the blue areas represent the observed range (minimal and maximal angles). The given angles: TA: Trunk Angle (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).

4. Discussion

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 §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 one hour 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, were 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, indicating that the muscle tension may not cause fatigue. The TRP-UP however shows a MVC over 5%, indicating that fatigue may occur in the long term in the shoulder-neck region.

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, were neck support benefitted the perceived comfort of most subjects. Stability offered by support of a headrest may avoid continuous corrections by the neck to maintain stability, as (among other) breathing, blood pumping and micro limbs 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 actually 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 subjects expect to experience. As shown by Bouwens, Schultheis, Hiemstra-van Mastrigt, and Vink (2017), it is not always possible to predict the experienced comfort based on expected comfort.

4.3. Posture

The posture between conditions B and C was significantly different. Without head support the head was found to be more upright and placed above the rotation axes of the neck. The reason for not finding any difference in the EMG (and the low EMG signals) may indicate 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 more 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. 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 40-44° 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.

4.4. Study limitations and suggestions

Due to the limited context of this study, muscle fatigue (Sjøgaard et al., 1986) and discomfort (G. Sammonds, Fray, & Mansfield, 2014; Vink, 2004; Vink, 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 (G. M. Sammonds, Fray, & Mansfield, 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.

5. Conclusion

In this study no significant difference in muscle activity (based on EMG) was 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. No significant difference in EMG and 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.

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 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.

Conflict of interests

This study was financially supported by Zodiac Aerospace. The sponsor had no influence on any decision nor execution of this study, including study design, data collection, analysis, data interpretation, writing and publication.

Acknowledgments

We want to thank ir. J.M.A. Bouwens, dr.ir. S. Hiemstra-van Mastrigt, ir. S. Akkerman and ir. D.M. Lips 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 Zodiac Seats US for lending the EMG equipment and financially supporting this study. And last but not least all the volunteers who were so kind to take part in this study.

References

Alamdari, F. (1999). Airline in-flight entertainment: the passengers' perspective. *Journal of Air Transport Management, 5*(4), 203-209.

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.

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.

Bouwens, J. M. A., Schultheis, U., Hiemstra-van Mastrigt, S., & Vink, P. (2017). Expected versus experienced neck comfort. *Submitted April 2016 at Human Factors and Ergonomics in Manufacturing & Service Industries*.

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.

Dalassio, D. J. (1980). *Wolff's Headache and Other Head Pain*. Oxford: Oxford University Press.

Davis, J. F. (1959). *Manual of surface electromyography*: Wright-Patterson Air Force Base, Ohio. Aerospace Medical Laboratory.

Delleman, N. J., Haslegrave, C. M., & Chaffin, D. B. (2004). *Working Postures and Movements*: CRC Press.

Delsys. (2012). Trigno Wireless System User's Guide. Retrieved from 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.

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.

Filho, N. M., Coutinho, E. S., & e Silva, G. A. (2015). Association between home posture habits and low back pain in high school adolescents. *European Spine Journal, 24*(3), 425-433.

Franz, M., Durt, A., Zenk, R., & Desmet, P. M. (2012). Comfort effects of a new car headrest with neck support. *Appl Ergon, 43*(2), 336-343. doi:10.1016/j.apergo.2011.06.009

Goossens, R. H. M., Snijders, C. J., Roelofs, G. Y., & Buchem, F. V. (2003). Free shoulder space requirements in the design of high backrests. *Ergonomics, 46*(5), 518-530.

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.

Hiemstra-van Mastrigt, S. (2015). *Comfortable passenger seats: Recommendations for design and research*. Delft: Delft University of Technology.

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.

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.

Keshner, E., Campbell, D., Katz, R., & Peterson, B. (1989). Neck muscle activation patterns in humans during isometric head stabilization. *Experimental brain research, 75*(2), 335-344.

Kilincsoy, Ü., Wagner, A., Bengler, C., Bubb, H., & Vink, P. (2014). *Comfortable rear seat postures preferred by car passengers.* Paper presented at the 5 th International Conference on Applied Human Factors and Ergonomics.

Knijnenburg, R. (2005). *Future passengers side truck seat for DAF*. Confidential graduation report. Industrial Design Engineering. Delft University of Technology. Delft, The Netherlands.

Konrad, P. (2005). The abc of emg. *A practical introduction to kinesiological electromyography, 1*, 30-35.

Kroemer, K. H. E., & Hill, S. G. (1986). Preferred line of sight angle. *Ergonomics, 29*(9), 1129-1134.

Letizi, J. (2016). [Personal communication, Delsys EMG training].

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.

Lockhart, R. D., Hamilton, G. F., & Fyfe, F. W. (1972). *Anatomy of the human body*: Lippincott, New York.

Mayoux Benhamou, M. A., Revel, M., & Vallee, C. (1995). Surface electrodes are not appropriate to record selective myoelectric activity of splenius capitis muscle in humans. *Experimental brain research, 105*(3), 432-438.

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.

Murray, M., Lange, B., Nørnberg, B. R., Søgaard, 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), 198.

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.

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.

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.

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*(1), 92-101.

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.

Roebuck, J. A., Kroemer, K. H. E., & Thomson, W. G. (1975). *Engineering anthropometry methods* (Vol. 3): Wiley-Interscience New York.

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.

Sammonds, G., Fray, M., & Mansfield, N. (2014). Overall car seat discomfort onset during long duration driving trials.". *Advances in Physical Ergonomics and Human Factors: Part II, 15*, 25.

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.

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.

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, 128*(3), 475-484.

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.

Snijders, C. J., Nordin, M., & Frankel, V. H. (1995). *Biomechanica van het spier-skeletstelsel; grondslagen en toepassingen. Lemma, Utrecht.* Retrieved from

Soderberg, G. L. (1992). Recording techniques. *Selected topics in surface electromyography for use in the occupational setting: Expert perspectives*, 31-35.

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.

Stanton, N. A., Hedge, A., Brookhuis, K., Salas, E., & Hendrick, H. W. (2004). *Handbook of human factors and ergonomics methods*: CRC Press.

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.

Travell, J. (1967). Mechanical headache. *Headache: The Journal of Head and Face Pain, 7*(1), 23-29.

Travell, J. G., & Simons, D. G. (1992). *Myofascial pain and dysfunction: the trigger point manual* (Vol. 2): Lippincott Williams & Wilkins.

van Rosmalen, D. M. K., Groenesteijn, L., Boess, S. U., & 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.

van Rosmalen, D. M. K., Groenesteijn, L., Boess, S. U., & Vink, P. (2010). Eisen aan een loungestoel om naar een scherm te kijken. *Tijdschrift voor ergonomie, 2, 35, 4-10*.

van Veen, S. A., 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*: CRC press.

Vink, P. (2016). *Vehicle seat comfort and design*: TU Delft Library.

Vink, P., & Brauer, K. (2011). Aircraft interior comfort and design (ergonomics design management: theory and applications): CRC Press, Boca Raton.

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 Annual Meeting.

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.

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

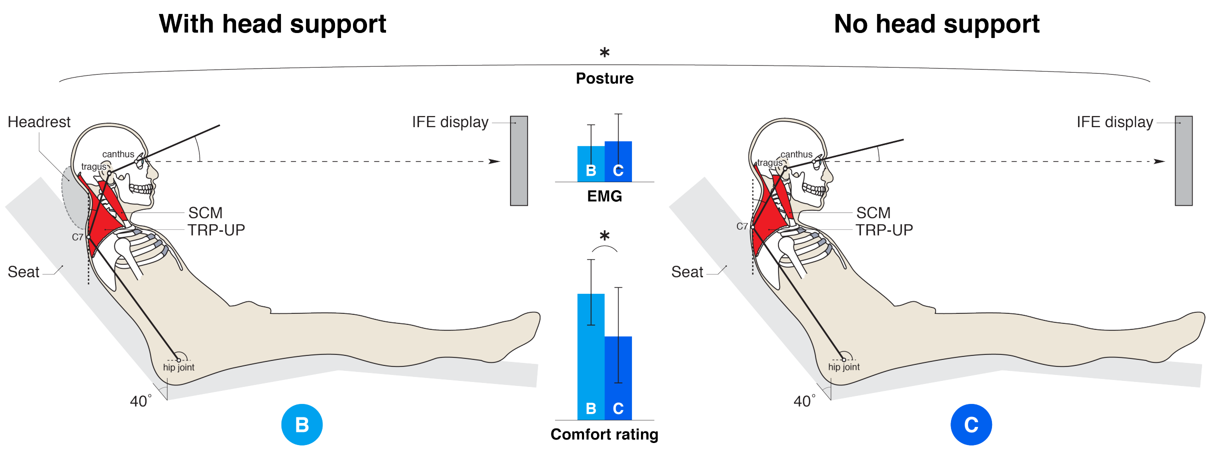
Zipp, P. (1982). Recommendations for the standardization of lead positions in surface electromyography. *European journal of applied physiology and occupational physiology, 50*(1), 41-54.

Highlights

- A slouched posture is preferred for watching IFE/TV
- Head support does not significantly lower muscle activity of neck muscles
- Humans tend to look for a head position with minimal muscle effort
- The expected comfort experience of the user is higher with head support

Graphical abstract

The significant difference in posture and the lack of significant difference in muscle activity (EMG) may indicate that humans tend to look for a head position with minimal muscle effort. A headrest may improve the expected comfort experience of the user.



Appendix D Reanalysis of inclination results of Smulders et al. (2016)

In the study of Smulders et al. (2016) the inclination of the legrest and backrest were determined, but not the head inclination. Therefore raw data – lateral pictures (see Figure 14.1) of the subjects in a business class seat (7070, made by Zodiac Seats US) – from this study was reanalysed. With the help of Adobe Illustrator an estimation of the head-neck angle (measured from the C7 to the tragus, see Figure 12.4) was measured. Results can be found in Table 14.1.

Figure 13.1 | Test setup of IFE inclination test

Two clear clusters in head position were observed. One cluster is where subjects flexed their head forward 38˚ on average, making no use of the headrest (which was parallel angled with the backrest, on average 32˚). Others extended their head 12˚ on average, resting it against the headrest and realign view towards the IFE screen by deorsumversion of the eye.

Table 14.1 | Angles C7-Tragus angle in degrees (incl. 3 deg. airplane angle) when watching IFE

Gender	Head flexed forward without headrest support	Head extended backwards resting on headrest
Male		24˚
Male		11˚
Male	48˚	
Male	26˚	
Male	43˚	
Female		9˚
Female		4˚
Female	38˚	
Female	33˚	
Female		10˚
Mean	38˚	12˚
Median	38˚	10˚
SD	9˚	7˚

Appendix E Ideation sketches

N.A. CONFIDENTIAL

Appendix F Z600 analysis and concepts

N.A. CONFIDENTIAL

Appendix G Zodiac Seats US analysis

13.1 The former client: Zodiac Seats US

13.1.1 Zodiac Aerospace: the mother company

Zodiac Aerospace is one of the world's biggest aeronautics equipment and systems manufacturers in the world, supplying parts and systems to big aircraft manufacturers like Boeing, Airbus and Embraer for commercial, regional and business aircrafts, as well helicopters and space applications. It is a French stock listed company, which has grown the last 25 years and expended their portfolio by acquiring other aeronautic companies. Currently it has 98 production sites and more than 32.000 employees around the world, with a diversity of specialties divided over five business segments: Zodiac Cabin & Structures, Zodiac Aircraft Systems, Zodiac AeroSafety, Zodiac Galleys & Equipment and Zodiac Seats.

13.1.2 Zodiac Aerospace's heritage

Zodiac Aerospace originally started as *Mallet, Mélandri and de Pitray*, founded in 1896 by Maurice Mallet and associates, producing hot-air balloons for sports and tourism. In 1911, the company adopted the name of *Zodiac* and expanded rapidly in the construction of airplanes and airships, especially in serving the Aérostation Maritime (the France Naval Balloon Command). Due to its military activities, Zodiac developed the first inflatable boat prototype in 1934, the predecessor what currently are known as *Zodiac* boats, which formed the foundation of the civil and military inflatable boat industry (Le, 2015; Zodiac Aerospace, 2012).

After WWII, Zodiac temporarily discontinued all its aeronautic activities and laid its focussing on recreational boating due to the boom in leisure activities, especially in its home country France in the 1960s. In 1966 Zodiac however revived its original core business by honouring a contract with CNES (Centre National d'Etudes Spatiales, the France National Centre for Space Studies) for the production of a meteorological balloon. In the 1960's and 70's Zodiac expanded internationally by opening subsidiaries Zodiac Española and Zodiac North America (Le, 2015; Zodiac Aerospace, 2012), making it an international player.

In 1973 the company experienced serious financial difficulties. Under lead of its new CEO and support from shareholders and the French Institute for Industrial Development, the company recovered in 1977. The acquisition of Aérazur Constructions Aéronautiques in 1987 and EFA in 1979 led to a real aeronautics branch. Zodiac continued its development in both marine and aerospace and continued its growth by acquiring multiple maritime and civil aviation related companies from 1981 till 2006, among others aircraft seat manufacturer Weber Aircraft in 1992 (nowadays known as Zodiac Seats US, see §0).

In 2007 the Zodiac Group sold its marine branch and by 2008 it renamed itself into Zodiac Aerospace. The company strengthened its position in the cabin interiors segment by acquiring the Dutch company Driessen (leading manufacturer of galleys for single aisle aircraft, trolleys, containers and galley inserts), Adder (cabin separators) and TIA (electrical equipment for galleys, mainly for the business aircraft market) in 2008, and its systems segment by acquiring the Canadian company Cantwell Cullen & Co (cabling and interconnect systems) and the German company Sell GmbH (galleys for wide-bodied aircraft) in 2010. Still focussed on external growth, Zodiac Aerospace acquired IMS (IFE systems) in 2012, rebranding it Zodiac Inflight Innovations. With these acquisitions Zodiac Aerospace created a broad portfolio of integrated aircraft equipment and systems (Le, 2015; Wiki Commons, 2016b; Zodiac Aerospace, 2012).

13.1.3 Zodiac Seats: the seats business segment

Zodiac Aerospace's seats business segment Zodiac Seats comprises of six divisions – Zodiac Seats France, Zodiac Seats UK, Zodiac Seats US, Zodiac Seats Automotive and Zodiac Seats Shells – which develop, manufacture, certify and sell passenger seats for first-, business-, premium economy- and standard economy class, as well as technical seats for aircraft pilots, helicopters and flight crew (Le, 2015; Zodiac Aerospace, 2016b).

13.1.3.1 Zodiac Seats France

Zodiac Seats France (ZSFR) is the biggest division with the most comprehensive product range and with six locations in France and Germany. They develop and produce first class, business class and economy class seats, crew seats and helicopter seats. ZSFR has their own in-house R&D, engineering and certification departments as well as production facilities (Le, 2015; Zodiac Aerospace, n.d.).

13.1.3.2 Zodiac Seats UK

Zodiac Seats UK Ltd (ZSUK) is the premium division, which mainly focuses on the high-end seat market. They design and produce first, business and premium-economy seats in three locations. ZSUK is mainly an production location and does not have a proper R&D department (Le, 2015).

13.1.3.3 Zodiac Seats US

Zodiac Seats US LLC (ZSUS) is the second biggest division with its headquarters in Gainesville, Texas, USA and with satellite locations in Mexico and China. ZSUS mainly produces on short and long haul economy seats, but has some premium economy, business and first class seats in its portfolio (Le, 2015; Zodiac Aerospace, 2016b).

13.1.3.4 Zodiac Seats California

Zodiac Seats California LLC (ZSCA) specialises in regional aircraft passenger seats (Le, 2015) and has been a former satellite division of Zodiac Seats US LLC, but still has strong ties with its former Texan headquarters. It has its own R&D, engineering and manufacturing facilities and there are plans to set up a centralised R&D studio here for the entire Zodiac Seats business segment.

13.1.3.5 Zodiac Seat Shells US

Zodiac Seat Shells US LLC designs and manufactures (composite) shells – which are used in business and first class – for the other seat divisions. These shells are an integral part of business and first class seats, having a big influence on the entire look of the seat. They are mostly designed and fabricated customer specific with high (visual) quality demands (Le, 2015; Zodiac Aerospace, 2016a, 2016b). This branch however, faces difficulty with quality and lead-time.

13.1.3.6 Zodiac Seats Automotive

Zodiac Seats Automotive (formally known as Zodiac Airbags) may be a bit of the odd man out at an aerospace company. The company was acquired for its expertise in the production of air backs, which are also used in some business class and aircraft seats (Foreign Investment Promotion Agency Tunisia, 2016; Zodiac Aerospace, 2016b).

13.1.3.7 Zodiac Seats locations

Zodiac Seats France
- France (Colomiers, Issoudun, Pusignan, Roissy)
- Germany (Hamburg)

Zodiac Seats US
- United States (Gainesville TX, Seattle WA)
- Mexico (Chihuahua)
- China (Tianjin)

- Zodiac Seats California
  - United States (Rancho Cucamonga CA)

- Zodiac Seats Shells
  - United States (Santa Maria CA)

Zodiac Seats UK
- United Kingdom (Brackley, Camberley, Cwmbran)

Zodiac Seats Automotive
- Tunisia (Soliman)

13.1.4 Webber Aircraft: the origin of Zodiac Seats US

The origin of Zodiac Seats US goes all the way back to 1898 when Fred Weber purchased the Los Angeles Showcase Company in Los Angeles and changed the name in Weber Showcase and Fixture Company (Weber Aircraft LLC, 2000c; Weber Aircraft LP, 2002). The company grew over the year and a diversity of new divisions were added, including Weber Refrigeration (Los Angeles Times, 2016), Weber Logistics and Weber Aircraft in 1941 (Weber Aircraft LLC, 2000a). During WWII the company devoted its entire production for the war effort, for which it was awarded the Army and Navy 'E' of excellence with five starts (Weber Aircraft LLC, 2000b). Early products included “drop” fuel tanks, navigator’s tables, landing gear, bomb bay doors, and crew seats (Weber Aircraft LP, 2002).

Figure 13.6 | 'Weber Aircraft Division Produces For War', for Weber Showcase and Fixture Company Incorporated, showing an airplane diving down towards a banner featuring products the company produces, such as bomb bay doors, fire extinguishers, toilet seat covers and bombardier' s seats. Originally appeared on September 1942 in 'Aviation, Vol. 42, No. 06', published by McGraw-Hill Publishing Company (Weber Showcase and Fixture Company Inc., 1942).

After the war, Weber Aircraft expended the portfolio military crew seats and commercial crew seats. Over the years Weber Aircraft moved more and more into the increasing commercial market, expanding their portfolio with commercial passenger seats, galleys, lavatories, oxygen assemblies, engine power packs, cargo floor systems and airstairs (Weber Aircraft LLC, 2000b).

In the mid 60's Weber Showcase and Fixture Company was sold (Los Angeles Times, 2016) and Weber Aircraft LLC was established in 1968 as a division of Walter Kidde and Company Inc., which had its roots in the aviation industry by designing and manufacturing smoke detection and fire extinguishing systems for aircrafts (Kidde, 2016). By 1967 Weber Aircraft opened its second manufacturing plant in Gainesville Texas besides its Californian plant in Brea and headquarters in Fullerton (Flagg, 1992). In the 60's and 70's Weber worked on ejection seats for the USAF and later also for NASA (Weber Aircraft LLC, 2000a)), being one of the biggest players in this field. In the mid 90's however, the ejection seats were discontinued (Weber Aircraft LLC, 2000a).

In 1987 Kidde merged with Hanson Trust PLC (Associated Press, 1987; Flagg, 1992) and sold Webber Aircraft in 1992 to Air Cruisers Co. , which was a part of Groupe Zodiac (Flagg, 1992). In 2002 Weber Aircraft's HQ was relocated from California to the 500.000 ft^2 Gainesville Texas location. Under lead of Groupe Zodiac the Fullerton facility was merged with Monogram, which produced waste management systems, galleys, air stairs, and coffee makers (Weber Aircraft LP, 2002). This resulted in the focus on passenger seating. In 2010 the 80.000 ft^2 Chihuahua plant in Mexico was opened (Webber Aircraft LLC, 2010). In 2012 the companies name changed into Zodiac Seats US LLC under the group's rebranding program, initiated after the restructuring of the Zodiac Aerospace business units.

13.1.5 Zodiac Seats US LLC today

Zodiac Seats US is one of the biggest manufacturers of commercial aircraft seats for airlines and commercial aircraft manufacturers, which develops and produces mainly short and long haul economy, premium economy and business class seats, but has first class seats in its portfolio too. Its headquarters and primary manufacturing facility is located in Gainesville Texas, with final assembly lines also located in Rancho Cucamonga California, Tianjin China and component manufacturing and subassembly facility in Chihuahua Mexico (Zodiac Aerospace, 2016c).

ZSUS conducts most of the design and engineering process in house, from initial design and engineering till testing and certification. It however sometimes outsources aesthetic design to a design agency. Prior to the acquisition, Weber Aircraft was mainly an engineering and manufacturing facility (Le, 2015; Van der Klooster, 2015). Despite having an in-house R&D department and an Human Factors and Ergonomics department, seats are still engineering driven. Also design and ergonomics are involved very late in the development process. This makes seats very functional, but aesthetics and comfort are subject to improvement (Le, 2015) (see also chapter 9).

13.1.6 The Gainesville plant

Zodiac Seats US headquarters and primary manufacturing facility in Gainesville Texas exceeds 65.000 square meters, excising out of two main buildings. The north wing features engineering, certification and overhead (e.g. HR, finance, safety) offices, and a main hall with part production, part testing (of both in-house and bought parts), sub-assembly lines, spare parts supply and warehouse, testing labs (16G tests, Head Impact Criteria (HIC) tests, durability tests), the prototype shop and training classrooms. The south wing features an upholstery and parts warehouse, final assembly lines, repair shops and shipping in the main hall, with sales, marketing, legal offices and the Human Factors and Ergonomics lab. All indoor transportation is done manually with electric carts.

13.2 ZSUS strengths, weaknesses and competition

Expertise

- Economy class, long & short haul
- Business class, long & short haul
- Client specific design
- Engineering and certification

Strengths (based on Le (2015), Van der Klooster (2015), Lips (2017) and own insights)

- In house engineering
- In house FAA approved testing and certification
- In house structural strength and reliability testing
- In house model making shop
- Client specific designs
- Four parallel assembly lines, capable of assembling multiple models
- Large-scale production (650 PAX a day) with customer customisation capabilities
- Large patent portfolio
- Located next to airfield, allowing express delivery by air
- Located close to Interstate 35 and railway, allowing reliable road and rail transport
- Multiple assembly and support locations worldwide
- Large capital
- Well known brand in aviation (both as Webber Aircraft and Zodiac Aerospace)

Weaknesses (based on Le (2015), Van der Klooster (2015), Lips (2017) and own insights)

- Old fashioned corporate structure and mentality
- Engineering focused, limited knowledge on aesthetics and passenger comfort & experience
- Very conservative and thereby not that innovative (also impaired due to certification restrictions)
- Slow moving
- Client specific designs lead to high amounts of parts, affecting lead-time
- Remote location (unattractive for talented engineers, long distance to ship seats by road to clients)
- Lacking knowledgeable staff and qualified management
- Bad (negative) corporate culture and lack of trust (distrust between different departments and different groups of employees, island mentality, bad co-operation among departments/worker-groups)
- Lead-time and production issues
- Quality issues
- Marketing and sales driven innovation
- No in-house design department
- No scientific approach
- No in-house human factors and ergonomics department (discontinued since mid-2016)
- No visual identity in seats (opposed to competition like RECARO)
- Limited co-operation with other Zodiac Aerospace branches (ZSUS is focussed only on own results and limits sharing knowledge with other branches. In that sense it still sees itself as an independent entity, where co-operation would benefit the entire Zodiac group)

Main competitors

- B/E Aerospace
+ Large capital
+ Well known name
– Slow moving (big)
- RECARO Aircraft Seating
+ Visual identity in seats
+ Ergonomic and design driven innovation
+ Well known name
+ Fast moving (small size)
– Limited customisation

– Limited in capital
- Stelia Aerospace (Airbus Group), a merge of Aerolia and Sogerma

Major competitors
- Geven
- ZIM Flugsitz
- Thompson Aero Seating
- Aviointeriors
- Jamco
- Haeco
- Lufthansa Technik

Small competitors
- Pitch
- Avic aircraft equipment
- Optimares
- ST Aerospace
- Expliseat
- Cobraas
- TSI aviation seats
- ACRO aircraft seating

13.3 Further reading on ZSUS and ZSUS graduation projects

For further reading on Zodiac Seats US, the following graduation theses are recommended:
- Le (2015): *The design of a next generation Y class aircraft seat*.
- Lips (2017): *Design of a lightweight and comfortable aircraft seat*.

For further reading on other Zodiac Seats US graduation projects from the Delft University of Technology, the following reports are recommended:
- Akkerman (2016): *Improving Boarding Efficiency And Experience*
- Kühne (2015): *Design of an adjustable headrest enabling sideward leaning and seclusion on long-haul economy flights*
- Van der Klooster (2015): *New headrest concept with integrated IFE solution enhancing passengers' privacy - and in-flight experience*

Appendix H Interviews Cabin Crew

A selection of the transcripts of interviews with CC on galley and cabin processes, originally for a galley safety project for ZGEU by the author.

> *(....) Last time I had a passenger who lost something during the night; help them search. You will laugh definitely about this; the old business class seats on the 777 (we will get new ones); who whoever designed that..?! Well, you have your seat and your headset. Do you know where you have to put in your headset? (...) Nobody can find it, which is pretty logic. (...) And then you have here behind [your back], below [the input]. Then sometimes I say to passenger 'I am getting a bit intimate now'; then I hang almost in their crotch then. [laughs, shows how she uses the flashlight to show the plug-hole to the passenger]. The one who designed that, they have to send them to a penalty camp. That is really stupid. But, well.. I am not going to help standard, of course. (...) I then say 'yes, its done such stupid' and then I enlighten the plug to show them where they can find it. When you then know where to search for it, that already helps [passengers]. I use it very often!* – BC FA (2015):
>
> *(....) These are the new flat-bed seats. It has nothing to do with safety, but KLM advertises for two years already with flat beds. But now I already have had two flights without flat beds. It takes a long time to replace them, I understand that, but you get so much passengers which are angry because they expect those flat bed [seats]. Lastly I had a passenger [who said] "I have flew 60 times with you [KLM] last year, I only had a bed once". (...) They have not converted all yet. That is becoming a source of vexation. The newly converted ones, the 777, then you have six seats left before the economy class galley. We already get complaints about that. (...) These seats are behind the economy class galley. When boarding we can't reach them, because everybody gets in here. (...) Then you start up front. It is already the idea that the purser offers those in the back a drink, since they feel a bit lost there. And I have to admit, in the beginning [of getting used to the new aircraft] I did. (...) So they have constantly crew of the economy class passing by. Here you don't want to sit for all your money. I so much hoped those seats would not get here, but they did. They want 34 business class seats. And business class is almost always full. So I understand that. But these are not favourable seats. (...) At the Airbus 200 you have that too. And at the 300 they are all upfront. (...) But there you have so many; those people up there – we already have complaints about it – feel a bit lost. We start up front. In the past we started just like normal from the back, working towards the galley. But for passengers it feels more pleasing when they see you coming. So at my last trip, that part to Jakarta – you have to work like crazy, otherwise you don't make it – some people were sitting here too. At a certain moment a man came looking [for us]. Then we said: 'it takes the same time sir, but you don't see us [coming]. So that's just also something psychological; you would think 'they forget us'. But when you look up and you see me busy, you think 'oh, she is coming'. But when you don't see anybody [crew from business class], but at the same time people [crew of economy] passing by, than you think 'I don't get anything'. But it takes the same amount of time. It does not depend on their position; in the end it takes the same amount of time to reach them. (...) But it has been found that people dislike it emotionally. I understand that. And you have the noise. At a certain moment, you have to prepare for second service. You have to change oven inserts, change trollies which come often from the back, causing a lot of traffic back and fort. That's not a big deal, but it can't be done completely quiet. (...) But these people now get disturbed by something they normally.. well.. it stays an airplane, but I can imagine that when you pay such amount for.. that you are disappointed with those last seats. I also think these will become last saleable seats. But when it's full, it's full. Than also there people will be seated.* – BC FA (2015)

Based on these, the following insight was made:
It may be important for the BC cabin to clearly separate it in front of the EC or PEC cabin, to make sure BCP's do not get disturbed by EC galley processes, boarding EC passengers and make them feel a part of the entire BC cabin. Some airliners make the choice to create a separate and smaller BC section behind the EC galley to increase the amount of BC seats, but this may create bothersome traffic to BCP's by the EC galley. Also the separation from the main BC cabin can cause FA's to 'forget' their BCP's in the second smaller BC cabin. This altogether makes these well paying BCP's feel less appreciated (BC FA, 2015; Emery, 2017).

Appendix I The history and economics of classification

13.4 The first classification of aviation

In the early days of commercial aviation, there were no different classes. Flying itself was an expensive and thereby exclusive experience. A 1950's fare for a round-trip between NYC and London was $6.800 (adjusted for inflation). That is approximately the same price as a first class ticket today (Wendover Productions, 2017). Although the first class price, cabins were fitted with relative simple seats (Eisenbrand, 2004).

The first kind of classification emerged in the 40's and 50's, when significant amount of revenue of US airliners came from contracts with the US Postal Service to fly mail around the USA. These flights made multiple stops and flew on odd hours. Although these aircraft flew mainly mail, they still had a passenger's section. Flying over these routs took longer due to its multiple stops, but were cheaper, where 'premium' flights were direct flights. Although the travel time differed, the cabin experience itself was the same (Wendover Productions, 2017).

In the 50's IATA strongly regulated airfares, determining fixed ticket prices for each route. This made airliners compete on standards of service than on price, offering passengers more and more luxurious perks (Braggs, 2017a). In 1948 Capital Airlines introduced *coach class* on its busy New York-Chicago domestic air route to compete against the railways. For a 25-40% lower airfare, passengers sat in a DC-4 with a 60 instead of the normal 40 seat configuration, making it the first physical difference in class. Pan Am was already experimenting with lower fares over the Atlantic, seeing the possibility to develop a market for international air tourism. Initially Pan Am's quest for fare reduction was opposed by the ITATA cartel till Pan Am threatened to leave IATA. By the first of May 1952, the first *tourist class* flights took of from New York (Dierikx, 2008).

Figure 13.7 | First north atlantic tourist flight New York-Amsterdam by KLM, May 1st 1952 (Ogier, 2015)

Since 1952 IATA allowed airliners to sell the same seats for different prices, offering different kinds of tickets for different kind of passengers. *Standard class* tickets could be purchased any time and had some flexibility (e.g. ticket could be changed to another time of departure), which were ideal for business travellers. They typically do not pay for their own tickets and therefore do not mind the ticket price. They however require flexibility and the ability to buy a ticket last minute. *Tourist class* tickets were generally 32% below *standard*, but had to be booked in advance and had no flexibility (passengers had to take the exact flight they bought their ticket for). This was ideal for tourists, since they plan their trips in advance and the lower price made flying a more affordable (but still expensive) way of leisure travel. By 1953 the *tourist* ticket already resulted in 53% more passengers than in 1951 (Dierikx, 2008) and by 1957 tourist class fares made up 70% of all air travel (Braggs, 2017a).

Through this system, airliners created two classes based on what the customers needed and were willing to pay. Over the next decade, this was the only classification in aviation. However, this classification was only in the ticket, since the seat was the same.

13.5 The introduction of economy

By the end of the 50's airliners faced a challenge. Aircraft manufacturers developed bigger aircraft faster than airliners could recoup their investments. The past 10 years the amount of seats per aircraft had doubled and the introduction of jet-propelled aircraft would double that again. Airlines wondered how to fill those large aircraft and find use for their relatively new propeller aircraft, which were slower, but still pressing on the airliner's balance. Again under lead of Pan Am, by 1958 IATA agreed on the introduction of *economy class* – which was 20% below tourist class – to offer a new, cheaper way to fly. Due to the introduction of the jet, the amount of PAX became more important than the offer of luxury. To stress this, food services were minimised and pitch decreased (Braggs, 2017a; Dierikx, 2008). To make an even more clear distinction in class, airliners also emphasised on seating amenities in *first class*, by placing sleeperettes for more comfort (Eisenbrand, 2004). This meant that no longer ticket flexibility and price, but now the perks were defined by class (Braggs, 2017a; Dierikx, 2008).

Figure 13.8 | Economy class of KLM, 1958 (Ogier, 2015)

13.6 Rapid growth of discounted fares

The in 1969 introduced Boeing 747 'jumbo jet' offered more space and more seats. Airliners who experienced the rapid growth in the 60's rushed to place orders. However, due to increasing fuel prices and recession in the early 70's, airliners were facing high costs and low demands, leaving them with expensive empty planes. Airliners tried to lour in new customers with cheaper fares, while keeping the frequent flyers buying the full fare tickets for the same price. The cheaper fares solved the airlines' cash flow problems, but it made flying a miserable experience for its full fare frequent flyers, which started to complain. Airports got crowded, queues longer and boarding lounges overfull, making passengers spend more time at the airport. The once quiet and spacious lounges and aircraft cabins got filled with noisy and excited holidaymakers and their children. Not only that, they sat in the same seats frequent flyers paid significantly more for (Braggs, 2017b, 2017c).

Thanks to de-regulation in the USA by the Airline Deregulation Act of 1978, airliners got more freedom to charge different prices for different types of clients. Although some airliners offered first class tickets with more comfortable seats and cabin, the majority of the difference was the flexibility of the ticket. The airlines valued their full fare paying business customers and were worried about losing them, since they already started to buy *tourist* tickets, costing airliners a lot of revenue. Airliners realised they had to start treating full fare passengers differently than discounted fare passengers in *tourist* and *economy (Braggs, 2017b, 2017c)*.

13.7 The introduction of business class

In 1975 multiple airlines started to treat their full fare passengers different, by offering them a separate cabin directly behind first class (where it is more quiet than in the back due to the engines). This gave them the peace and quiet they craved for, since discounted passengers sat in the cabins in the back. These full fare cabins sometimes offered a different seat configuration and service. Some airliners also created separate counters and priority baggage services and offered lounge access. Bigger seating and legroom were introduced in 1979 and airliners started branding their full fare cabins *business class* (BC). Finally some airliners started to offer a different cabin experience with more luxurious seats and amenities.

13.8 The phasing out of first

In the 70's and 80's most airlines started phasing out first class, since the in 1969 introduced Concorde was expected to become the airplane for the rich and famous due to its supersonic speed, and started focussing on the middle tier of traveller. Airliners started competing over the full fare *business* class flyer by offering better amenities, services and bigger seats (see also §**Error! Reference source not found.**). Due to the failure of Concorde, a select group of airliners slowly started reincorporating first class in their sub-sonic aircraft, but the effect of Concorde can still be seen today. Many airliners who previously offered first class in their cabins have discontinued them ever since, putting focus on optimisation of *business class*. Today, only six transatlantic airliners still offer *first* and it is slowly disappearing. The reason? Costs.

The difference in seat and amenities between *economy* and *business* is huge (a cramped public transport seat vs. a bed in the sky), where the difference between *first* and *business* becomes thinner and thinner. Due to the battle for the business class traveller's favour (see §**Error! Reference source not found.**), *business* gained more and more the perks of *first*. It is hard for airliners to justify the higher ticket price for the limited difference between the two classes, although the cost to run a *first class* service is significantly higher for an airline (Sumers, 2017). When comparing the classes' revenue per square foot (see Table 14.2), *first* makes just more over *business* per ft^2, and that is only when all these tickets are sold. *First* also gains competition from private jets, since these get more affordable and safe significant time at the airport, making them an interesting alternative for *first* (Krupnick, 2015).

"You look at the value proposition and the cost differential, and the amount of real estate it takes up can hardly be justified. There's a very small market that sits between business class and a private jet

that wants to fly in first class." – Ben Smith, president of passenger airlines for Air Canada (Sumers, 2017)

Table 14.2 | Revenue per ft² on a British Airways Boeing 747-400 (V3) flying daily between London Heathrow and JFK New York. Prices are for a June 12-June 19 return flight as stated on May 2nd, 2017. Currency correction on May 2nd, 2017. (British Airways, 2017; Garcia, 2016; Seat Guru, 2016)

Class	Ticket	Seat space	Revenue per ft² (per m²)
Economy	€ 605,32	3.77ft2 (0,35m2)	€ 160,56/ft2 (€ 1.729,48/m2)
Premium Economy	€ 1.092,90	4.88ft2 (0,45m2)	€ 233,96/ft2 (€ 2.428,67/m2)
Business	€ 1.861,14	10.14ft2 (0,94m2)	€ 183,54/ft2 (€ 1.979,94/m2)
First	€ 2.378,46	12.07ft2 (1,12 m2)	€ 197,06/ft2 (€ 2.123,63/m2)

For these reasons, more and more airliners start replacing their *first class* with *business class* seats, simply since it makes more money (see also **Error! Reference source not found.**). Only a select amount of 'elite' airlines has further developing their *first* class experiences with extravagance, but even they are slowly replacing *first* for business (Sumers, 2017). The demand is simply too low and the seats too big and therefore not cost effective.

13.9 **Further reading**

For further reading on the history of aviation and aircraft seating, Eisenbrand (2004) and Dierikx (2008) are recommended. Eissenbrand elaborates on seating history, how seats evolved over the past decades into the minimalistic aluminium constructed, composite and plastic cladded and foam padded seats of today. Dierikx elaborates on the full history of aviation and the major impact it has on the worlds many historical events.

Appendix J Literature comparisons

13.10 Microclimate literature comparison

Table 14.3 | Overview of studies stating thermal neutral (TN) zone temperature ranges (based on Z. Lin and Deng (2008) and Flynn-Evans et al. (2016))

Source	Process	Condition	Sample	Thermal neutral zone
Coenen (2006)	Based on unknown literature study	N.a.	N.a.	27-29°C
Candas et al. (1979) (as cited by Muzet et al. (1984))	Unknown	Ambient temperature between 16-25°C	Unknown	28.6-30.9°C
Okamoto et al. (1997)	Thermometer under blanket	Ambient temperature between 22-23°C, humidity 50-60%	n=6	26-32°C
Haskell et al. (1981)	Adjusting room temperature per night	Naked with shorts. Ambient temperature set at 21, 24, 29 (TN), 34 and 37°C	n=6	29°C
Goldsmith and Hampton (1968)	[1]	[1]	[1]	34-36°C
Vokac and Hjeltnes (1981)	[1]	[1]	[1]	34-36°C
Candas et al. (1982)	[1]	Naked	[1]	32°C
Macpherson (1973)	[1]	Naked	[1]	29-32°C
Karacan et al. (1978)	[1]	Covered	[1]	22.2°C
Palca et al. (1986)	[1]	Naked	[1]	29°C
Sewitch, Kittrell, Kupfer, Reynolds (1986)	[1]	Covered	[1]	20-22°C
Di Nisi et al. (1989)	[1]	Naked	[1]	30°C
Dewasmes et al. (2000)	[1]	Naked	[1]	28°C
Lan et al. (2014)	Adjusting room temperature per night	Ambient temperature set at 23, 26, 30°C.	n=18	26°C
Sewitch, Kittrell, Kupfer, and Reynolds (1986)	[1]	[1]	[1]	[1]
Kingma et al. (2014)	[1]	Ambient thermoneutrality with insulation present (e.g. clothing/bedding)	[1]	14.8-24.5°C
Z. Lin and Deng (2008)	[1]	Ambient thermoneutrality (clothed)	[1]	20-22.2°C
Kingma et al. (2014)	[1]	Ambient thermoneutrality for maintaining skin temperature in absence of clothing and bedding	[1]	27.9-28.5°C
Z. Lin and Deng (2008)	[1]	Ambient thermoneutrality (semi-nude)	[1]	28-32°C
Okamoto-Mizuno and Mizuno (2012)	[1]	Ambient thermoneutrality (semi-nude)	[1]	29°C

[1] Author did not check this yet.

13.11 Pressure comparison between seating and lying

Table 14.4 | Advised pressure distribution for seat and sleeping.

Posture	Advised pressure distribution for sitting in a seat	Weight percentages of the human body regions when lying down
Source	Hartung (2006); Raphael Zenk (2008); R Zenk et al. (2012)	Yoshida, Kamijo, and Shimizu (2012)
Head	n.a.	8%
Back	20-50%	33%
Buttocks	50-60%	44%
Legs	10-30%	15%

13.12 Eye deorsumversion literature comparison

Table 14.5 | Relaxed deorsumversion of the eye (relaxed line of sight) without head movement

Reference	Sample size (n)	Condition	Mean eye-horizon angle	Comfortable range
Pheasant and Haslegrave (2005)				-10° / -15°
Tilley (1993)			-15°	
Mon-Williams et al. (1999)	n=12	Fixed head position, with an 65 cm arc	-16.75° ± 4.9 [1]	-19° / -36°

[1] Adjusted for 10° EEL

Table 14.6 | Recommended visual angle and distance for displays

Reference	Sample size (n)	Activity	Eye-screen distance (cm)	Eye-horizon angle
Grandjean, Hünting, and Pidermann (1983)	n=	VDU	76 ± 7.5	-9° ± 4.5
Jaschinkski, Heuer, and Kylian (1999)	n=	VDU	80	-8°
Brown and Schaum (1980) (as cited in Pheasant and Haslegrave (2005))	n=	VDU	62.4	-18°
Yoichi et al. (2012)	Unknown	TV	[2]	-0°

[2] Dependent on screen size

Table 14.7 | Maximal deorsumversion of the eye without head movement

Reference	Sample size (n)	Condition	Eye angle below horizon
Tilley (1993)			35°
Taylor, Parker Jr, and West (1973)			66°
Weston (1953)			24-27°
Mon-Williams et al. (1999)	n=12	Fixed head position, with an 65 cm arc	53.33°[3]

[3] Adjusted for 10° EEL

This master graduation thesis explores the possibilities for improving the comfort experience for watching in flight entertainment (IFE) and sleeping in premium aircraft seats trough headrest design.

It contains scientific studies, comes with industry recommendations and multiple designs. Further research and development is proposed of a premium economy headrest supporting for sleeping with a limited recline and head-neck support for watching IFE in premium cabins.