Aircraft interiors, effects on the human body and experienced comfort

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Aircraft interiors, effects on the human body and experienced comfort

Shabila Anjani

Aircraft interiors, effects on the human body and experienced comfort

Dissertation

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Aircraft interiors, effects on the human body and experienced comfort

Contents

Summary

Summary

Have you ever sat in a cramped airplane? Sitting shoulder-to-shoulder with limited legroom might not be a comfortable experience while flying in an airplane. Human anthropometrics is important to consider when designing for interiors used by a large population. To accommodate people of all sizes, a certain minimum pitch and width are needed in an aircraft seat should be made in the pitch and width of an aircraft seat. However, increasing pitch and width is probably not the best for airline revenues, as an increasing pitch will reduce the number of passengers and thereby the income. Therefore, other solutions are needed as well. This PhD research can be helpful for airlines to find the optimum as background information is gathered about the level of comfort experienced by passengers in different seat sizes.

The aim of this research is to understand how to predict comfort (C) by looking at the physical entities (PE), its interaction (I) with the human, the human body effects (H) and perceived effects (P). The application area of the model is the aircraft interior. Therefore, the research objective of this PhD thesis is to increase aircraft passengers' comfort by creating knowledge on those physical entities that predict comfort. This research is split into 3 phases, exploring each step between PE and C. An overall application of these phases will be discussed towards the end.

Phase 1 (discussed in Chapter 2) is a study on different seat spaces of an aircraft (PE). It will be explored focusing on interaction (I) between different people and the interior, resulting in comfort (C). The study with a variation in seat pitches found that among the 294 passengers with a higher popliteal height, a longer buttock-knee depth, a higher eye height sitting and a higher sitting height show more discomfort with a reduced pitch then shorter passengers. Another analysis of this interaction between the human and the seat space demonstrated a significant relationship between seat pitch and comfort as well as discomfort. Additionally, it was found that the mean rank of the discomfort of each pitch size for the middle seat was higher than the window and aisle seat. In a second study with 311 passengers, the seat width was varied. The addition in seat width reduced discomfort at the shoulders, knees, and lower legs and feet. Regarding the anthropometric measurements, participants with a smaller hip-breadth felt more comfortable while sitting in the 18-inch-wide seat, which highlights the importance of freedom of movement. A larger space resulted in more comfort. The study also showed that to reach a similar level of comfort, increasing the width of a 17-inch-wide seat by one inch might be more efficient than increasing the pitch four inches.

In phase 2 (discussed in Chapter 3), the results of phase 1 are further explored by measuring the human body effects (H) (e.g. heart rate variability (HRV)) and the relationship to comfort. HRV was measured for passengers during 2-hours of sitting in an airplane seat. A certain timeline with different tasks, both with and without the use of the tray-table was performed to simulate an aircraft travel journey. Interestingly, the seat with the least space did not perform the worst in this study, which might be caused by the tray table. This study found that most HRV parameters are related to comfort, but not so much to discomfort, probably because the heart rate is more related to emotions than to the lack of physical space. This could indicate that HRV could be used as a human-body effect indicator in predicting comfort as comfort was found to be more related to HRV parameters that are correlated to well-being, emotions and the psychological state. Other studies showed that discomfort is more related to physical parameters like pressure distribution. Additionally, subjective discomfort was found to increase over time in line with some measurements of the HRV. Over all parameters, the HRV parameters: standard deviation of the time interval between successive normal-to-normal heartbeats (SDNN); high frequency of the heart rate (HF); and standard deviation of the projection of the Poincaré plot along the line of identity (SD2) seem promising as it has the strongest relationship with comfort and it is fairly easy to record where the changes over time could be detected.

Phase 3 (discussed in Chapter 4) explores comfort questionnaires as a methodology to measure perceived effects (P). An overview of subjective assessment methods of comfort is presented in the list of Preferred Comfort Questionnaires (PCQ) of product design. Fifteen candidate questionnaires on comfort were selected and ranked by 55 comfort researchers and practitioners in a workshop. A PCQ for comfort research was generated for five proposed application fields and four design phases, the preferred questionnaires were highlighted and categorized into four categories: preferred questionnaire, suitable for less prior training, suitable for fast completion and generally applicable, which led to a list of PCQ for Product Design. This PCQ list can be used as an instrument to help researchers in selecting questionnaires for comfort research in product design for a specific situation.

An application of the results of the study to create knowledge on physical entities (PE) that predict comfort (C) is explored by giving the possibility to aircraft interior experts to use the knowledge generated (discussed in Chapter 5). Aircraft interior experts were asked to make floor plans with comfort as a consideration. The results of the experts are then compared to the layouts generated by computational algorithms where rotations were allowed without considering comfort. Overall, experts were better at using comfort knowledge and are more out-of-the-box in making future floor plans though some ideas did not meet the regulations. The results of the computer program had higher potential revenue by adding business class seats, and it also resulted in optimal use of the space and would ensure all regulations are met, though some floor plans contained rotated seats where the comfort level is still unknown.

Experiments with a variety of participants, products, and tasks were conducted and measurements of the interaction, human body effects and perceived effects were recorded. These studies prove that indeed comfort and discomfort are a result of the interaction, human body effects and perceived effects, and these aspects could be used as a predictor of comfort. And comfort can be predicted, for instance, based on pitch and width related to anthropometry, but also based on HRV parameters. The results of the quantitative results of the studies showed a transition of comfort and discomfort in two different axes, as also mentioned in the literature. Time was a factor that was also added in the research of Chapter 3. Since there is a change over time in this comfort and discomfort rating, the third axis of time could be added to this interaction.

This PhD has basic information which can be used in future studies with advanced sensors and technology enabling researchers and manufacturers to gather more human data without interfering with the participant. This can contribute to reducing the problem by continuously asking for participants to self-assess their comfort to measure the current comfort status. The use of cameras for observing participants can overcome this problem which could be used in future studies. Smart analysis like recording the human fidgeting and studying HRV parameters are promising and could be further explored as new sensors appear bringing new possibilities to make use of this data. Discomfort might be measured by pressure sensors in the seat and comfort by HRV parameters, which brings us closer to the prediction of comfort and discomfort by just recording.

Finally, this research proves that physical entities can predict comfort, and observing the interaction and recording human body effects like HRV can predict comfort as well. Additionally, there are good questionnaires available for many situations predicting and recording comfort. Designers can use these methods to create a better functional aircraft interior which then increases passenger comfort.

Samenvatting

Heb je ooit krap in een vliegtuig gezeten? Het schouder aan schouder zitten met beperkte beenruimte is misschien geen comfortabele ervaring in een vliegtuig. De menselijk maat (antropometrie) is hierbij lastig omdat er veel verschillen tussen mensen zijn. Om mensen van verschillende omvang en lengte tegemoet te komen, zou er een minimum gesteld moeten worden aan stoelbreedte en beenruimte van een vliegtuigstoel. Teveel ruimte is voor de passagier fijn, maar is voor de luchtvaart maatschappij niet het beste vanwege afname van de inkomsten. Daarom zijn nu in de luchtvaartwereld ook andere oplossingen in ontwikkeling, zoals dunnere rugleuningen. Het is ook de vraag wat het beste optimum is tussen de comfortwens van de passagier en de inkomsten van de luchtvaartmaatschappij. Dit Promotieonderzoek is voor luchtvaartmaatschappijen zeer relevant omdat data worden verzameld over comfort bij verschillende inrichtingen. Het doel van dit onderzoek is om te begrijpen hoe comfort (C) kan worden voorspeld door te kijken naar de fysieke entiteiten (FE), de interactie met de mens (I), de lichaamseffecten van de mens (L) en door de mens waargenomen effecten (W). Het toepassingsgebied van het model is het interieur van het vliegtuig. Daarom is het onderzoeksdoel van dit proefschrift: het verhogen van het comfort van vliegtuigpassagiers door kennis over de fysieke entiteiten van het interieur, die comfort voorspellen. Dit onderzoek wordt beschreven in 3 fasen gericht op respectievelijk I, L en W. Een algemene toepassing van deze fasen zal tegen het einde worden besproken.

In het eerste onderzoek (hoofdstuk 2) werd de 'pitch' gevarieerd en bij 294 passagiers werd het comfort vastgesteld. 'Pitch', dat is de afstand tussen een punt op de stoel tot het zelfde punt op de stoel ervoor. De kortere 'pitch' bleek vooral een probleem voor mensen met een hogere knieholte, een langere bil-kniediepte, een hogere ooghoogte en een hogere zithoogte. Een andere analyse toonde aan dat er een significante relatie is tussen zitplaatsruimte en comfort. Bovendien werd geconstateerd dat het gemiddelde discomfort voor de middelste stoel hoger was dan die van het raam en het gangpad. In een tweede onderzoek dat is gedaan met 311 passagiers werd zitbreedte gevarieerd en het effect ervan op comfort werd gemeten en vergeleken met de vorige resultaten. De brede stoel verminderde het ongemak op de schouders, knieën en onderbenen en voeten. Wat betreft de antropometrie, voelden deelnemers met een kleinere heupbreedte zich comfortabeler in de 18-inch brede, wat het belang van bewegingsvrijheid benadrukt. De studie toonde ook aan dat om een vergelijkbaar comfortniveau te bereiken, het vergroten van de breedte van een 17-inch brede stoel met een inch efficiënter is dan het verhogen van de pitch met één inch.

In het tweede onderzoek (beschreven in hoofdstuk 3) zijn de effecten in het menselijk lichaam (H) via hartslagvariabiliteit (HRV)) gemeten en gerelateerd aan comfort en discomfort. HRV werd gemeten bij passagiers gedurende 2 uur zittend in een vliegtuigstoel. Interessant genoeg presteerde de stoel met de minste ruimte niet het slechtste, wat mogelijk veroorzaakt is door de 'traytable'. Uit deze studie bleek dat de meeste HRV-parameters verband houden met comfort, maar niet zozeer met discomfort, waarschijnlijk omdat de hartslag meer gerelateerd is aan emoties dan aan de fysieke aspecten. Dit zou erop kunnen duiden dat HRV kan worden gebruikt als indicator voor het voorspellen van comfort. Andere onderzoeken toonden aan dat discomfort meer verband houdt met fysieke parameters zoals drukverdeling in het zitvlak.

In het derde onderzoek (besproken in Hoofdstuk 4) zijn comfortvragenlijsten bestudeerd, wat verband houdt met de waarneming (W). Er zijn veel vragenlijsten over comfort beschikbaar, maar de vraag is welke de beste zijn. In een onderzoek met 55 experts op het terrein van comfort zijn de beste geselecteerd. Een overzicht van subjectieve beoordelingsmethoden voor comfort is in dit proefschrift gepresenteerd in de lijst van Preferred Comfort Questionnaires (PCQ). Er werd een PCQ voor comfortonderzoek gegenereerd voor vijf voorgestelde toepassingsgebieden en vier ontwerpfasen, de geprefereerde vragenlijsten zijn voor iedere situatie in dit proefschrift te vinden. Deze PCQ-lijst kan worden gebruikt als instrument om onderzoekers te helpen bij het selecteren van vragenlijsten voor comfortonderzoek in een productontwerpproces voor een

specifieke situatie.

Een toepassing van de resultaten van de studie van fysieke entiteiten (FE) die leiden tot comfort (C) is onderzocht door experts die het interieur van vliegtuigen inrichten. Zij kregen de mogelijkheid om de gegenereerde kennis te gebruiken (dit staat in Hoofdstuk 5). Deskundigen op het gebied van vliegtuiginterieur werden gevraagd om plattegronden te maken gericht op comfort. De resultaten van de experts zijn vervolgens vergeleken met de lay-outs die zijn gegenereerd door computeralgoritmen. Over het algemeen waren experts beter in het gebruik van comfortkennis en zijn ze meer out-of-the-box in het maken van toekomstige plattegronden, hoewel sommige ideeën tegen de certificatie regels stootten.

Er zijn in dit proefschrift verschillende experimenten uitgevoerd met verschillende deelnemers, producten en taken gericht op comfort. Ook de interactie is gemeten tussen mens en omgeving en het effect in het menselijk lichaam. De vragenlijst is gebruikt om de waargenomen effecten te registreren. Deze onderzoeken tonen aan dat comfort en discomfort (ongemak) inderdaad te beïnvloeden zijn door de interactie (I) te wijzigen, gerelateerd zijn aan effecten in het menselijk lichaam (L)(hartslag) en waargenomen (W) effecten. Deze fenomenen kunnen worden gebruikt als een voorspeller van comfort. Comfort kan worden voorspeld, bijvoorbeeld op basis van ‘pitch’ en stoelbreedte, maar ook op basis van HRV-parameters. Daarnaast zijn er voor veel situaties goede vragenlijsten beschikbaar die comfort voorspellen en vastleggen. Ontwerpers kunnen deze methoden gebruiken om een beter functioneel vliegtuiginterieur te creëren dat vervolgens het passagierscomfort verhoogt.

Ringkasan

Pernahkah Anda duduk di pesawat yang sempit? Duduk berhimpitan bahu dengan ruang kaki terbatas tentu bukan pengalaman yang nyaman. Dimensi tubuh (antropometri) manusia sangatlah penting dalam mendesain interior yang bisa digunakan untuk populasi besar. Agar dapat mengakomodasi semua orang dengan berbagai ukuran tubuh, diperlukan jarak minimum antara kursi dan lebar minimum kursi yang sesuai. Namun, menambah jarak dan lebar kursi mungkin bukan pilihan yang terbaik dari segi pemasukan maskapai penerbangan. Karena hal ini menyebebabkan jumlah penumpang berkurang, yang juga akan berimbas pada berkurangnya pendapatan. Oleh karena itu, diperlukan solusi lain. Studi doktoral ini dapat membantu maskapai penerbangan dalam menentukan solusi optimal, dengan memberikan informasi tentang tingkat kenyamanan penumpang saat duduk di kursi dengan dimensi yang berbeda-beda, sebagai latar belakang pengambilan keputusan.

Tujuan dari penelitian disertasi doktoral ini adalah untuk mengetahui bagaimana cara memprediksi kenyamanan (C) dengan melihat entitas fisik (PE), interaksinya dengan manusia (I), efek terhadap tubuh manusia (H) dan kenyamanan yang dirasakan (P). Beberapa literatur mengenai model tentang kenyamanan digunakan dalam penelitian ini, dimana kenyamanan dan ketidaknyamanan berada pada dua sumbu yang berbeda. Tidak adanya ketidaknyamanan belum tentu menghasilkan kenyamanan. Model ini akan diterapkan untuk bidang interior pesawat terbang. Sehingga dari penelitian ini diharapkan dapat diperoleh pengetahuan tentang entitas fisik yang memprediksi kenyamanan. Penelitian ini dibagi dalam 3 bagian, masing-masing membahas tiap tahap diantara PE dan C. Kemudian, aplikasi keseluruhan hasil akan dibahas pada bagian akhir.

Tahap 1 (dibahas dalam Bab 2) adalah penelitian yang dilakukan dengan berbagai ukuran kursi dalam pesawat terbang (PE). Pembahasan ini akan berfokus pada interaksi (I) antara manusia dan interior pesawat, yang berakhir dengan kenyamanan (C). Sebuah penelitian dengan 294 peserta dilakukan menggunakan berbagai ukuran jarak antar kursi. Ditemukan bahwa untuk penumpang dengan tinggi lipat lutut (popliteal height) yang tinggi, jarak antara lutut dan pantat (buttock to knee length) yang besar, tinggi mata pada posisi duduk (eye height sitting) yang tinggi, dan tinggi badan pada posisi duduk (sitting height) yang tinggi, maka tingkat kenyamanan akan sangat berkurang dengan dikuranginya jarak antar kursi, apabila dibandingkan dengan penumpang dengan ukuran yang lebih kecil. Analisa lain menunjukkan adanya hubungan signifikan pada interaksi antara jarak antar kursi dengan kenyaman dan ketidaknyamanan penumpang. Selain itu, ditemukan pula bahwa rata-rata ketidaknyamanan paling besar adalah untuk kursi yang berada di tengah, dibandingkan dengan kursi yang berada di dekat jendela maupun yang di dekat lorong. Hal ini berlaku untuk semua variasi jarak antar kursi. Penelitian kedua dilakukan dengan 311 penumpang dengan membandingkan lebar kursi yang berbeda. Penambahan lebar kursi mengurangi ketidaknyamanan penumpang pada bagian bahu, lutut, serta betis dan kaki. Apabila memperhatikan antropometri tubuh manusia, penumpang dengan lebar panggul (hip breadth) yang kecil merasakan perbedaan yang sangat besar saat duduk di kursi dengan lebar 18 inchi. Hal ini menyoroti perlunya kebebasan gerak untuk penumpang. Ruang gerak yang lebih besar mengakibatkan tingginya kenyamanan. Studi ini juga memperlihatkan bahwa untuk mencapai tingkat kenyamanan yang hampir sama, pilihan untuk melebarkan kursi 17 inchi sebanyak 1 inchi adalah pilihan yang lebih efisien dibandingkan dengan menambah jarak antar kursi sebanyak 1 inchi.

Pada tahap 2 (dibahas pada Bab 3), hasil dari tahap 1 akan dibahas lebih lanjut dengan mengukur efek terhadap tubuh manusia (H) (contohnya adalah variabilitas denyut jantung (heart rate variability/HRV) dan hubungan dengan kenyamanan manusia. HRV diukur pada penumpang pesawat terbang dalam keadaan duduk dengan durasi 2 jam. Penelitian ini menggabungkan beberapa kegiatan yang biasa dilakukan di pesawat terbang. Sebagian kegiatan dilakukan dengan menggunakan meja, dan lainnya tanpa meja. Menariknya, kursi dengan dimensi paling kecil bukan merupakan kursi dengan nilai terendah pada penelitian ini yang mungkin disebab-

kan karena penggunaan meja lipat pesawat. Penelitian ini menemukan bahwa hampir semua parameter pada HRV berhubungan dengan kenyamanan, sebaliknya tidak terlalu banyak berhubungan denga ketidaknyamanan. Hal ini mungkin terjadi karena denyut jantung hubungannya lebih dekat dengan emosi dibandingkan dengan kurangnya ruang gerak fisik.

Hal ini dapat menunjukkan bahwa parameter HRV dapat digunakan sebagai indikator pada efek tubuh manusia dalam memprediksi kenyamanan karena parameter HRV berkorelasi dengan well-being, emosi, dan keadaan psikologis. Studi lain menunjukkan bahwa ketidaknyamanan lebih terkait dengan parameter fisik seperti pendistribusian tekanan. Selain itu, ketidaknyamanan subjektif ditemukan meningkat seiring dengan beberapa pengukuran variabilitas denyut jantung. Secara keseluruhan, 3 parameter HRV: standar deviasi interval waktu antara detak jantung normal ke detak jantung normal berikutnya (SDNN); frekuensi tinggi dari detak jantung (HF); dan standar deviasi dari garis proyeksi pada plot Poincaré di sepanjang garis identitas (SD2), tampak menjanjikan karena memiliki hubungan paling kuat dengan kenyamanan dan dapat mendeteksi perubahan dari waktu ke waktu.

Tahap 3 (dibahas dalam Bab 4) menyelidiki kuesioner kenyamanan sebagai metodologi untuk mengukur efek yang dirasakan (P). Gambaran umum tentang metode-metode penilaian subjektif terhadap kenyamanan disajikan dalam daftar Pilihan Terbaik untuk Kuesioner Kenyamanan atau Preferred Comfort Questionnaires (PCQ) untuk Desain Produk. Lima belas kandidat kuesioner tentang kenyamanan dipilih dan diberi peringkat oleh 55 peneliti dan praktisi dibidang kenyamanan dalam sebuah forum diskusi. PCQ untuk penelitian tentang kenyamanan dibuat untuk lima bidang aplikasi dan empat fase desain. Kuesioner terpilih kemudian dikategorikan ke dalam empat kategori: kuesioner pilihan terbaik, kuesioner yang cocok untuk digunakan tanpa/sedikit pelatihan sebelumnya, kuesioner yang cocok untuk diselesaikan secara cepat dan kuesioner yang bisa berlaku umum. Hasil ini kemudian mengarah kepada dibentuknya PCQ untuk Desain Produk. PCQ ini dapat digunakan sebagai instrumen untuk membantu peneliti dalam memilih kuesioner penelitian kenyamanan dalam desain produk untuk situasi-situasi tertentu.

Penerapan hasil studi untuk menciptakan pengetahuan tentang entitas fisik (PE) yang memprediksi kenyamanan (C) dibahas dalam Bab 5. Penelitian ini memberikan opsi kepada pakar interior pesawat untuk menggunakan pengetahuan tentang kenyaman yang dihasilkan pada bab-bab sebelumnya. Para pakar interior pesawat diminta untuk membuat tata letak kursi dalam pesawat dengan pertimbangan kenyamanan. Hasil para pakar kemudian dibandingkan dengan tata letak yang dihasilkan oleh algoritma komputer di mana rotasi diperbolehkan tanpa mempertimbangkan kenyamanan. Secara keseluruhan, para ahli lebih baik dalam menggunakan pengetahuan tentang kenyamanan dan mempunyai ide-ide kreatif dalam membuat tata letak kursi untuk penerbangan dimasa depan, meskipun beberapa dari ide ini bertentangan dengan peraturan yang berlaku saat ini. Hasil dari program komputer memiliki potensi pendapatan yang lebih tinggi dengan menambahkan kursi kelas bisnis. Penggunaan komputer menghasilkan penggunaan ruang yang optimal dan akan memastikan semua peraturan terpenuhi, meskipun beberapa denah lantai berisi kursi diputar, dimana tingkat kenyamanan kursi tersebut masih belum diketahui.

Interaksi, efek tubuh manusia dan efek yang dirasakan diukur dengan membuat eksperimen dengan berbagai peserta, produk, dan tugas. Studi ini membuktikan bahwa kenyamanan dan ketidaknyamanan adalah hasil dari interaksi, efek tubuh manusia dan efek yang dirasakan, dan aspek-aspek ini dapat digunakan untuk memprediksi kenyamanan manusia. Dan kenyamanan ini bisa diprediksi dengan berbagai dasar, sebagai contoh dengan membandingkan jarak antar kursi dan lebar kursi dengan antropometri tubuh manusia, dan bahkan parameter variabilitas denyut jantung juga bisa menjadi dasar prediksi ini. Hasil penelitian kuantitatif menunjukkan adanya transisi kenyamanan dan ketidaknyamanan dalam dua sumbu berbeda, sebagaimana juga disebutkan dalam literatur. Waktu adalah faktor yang juga ditambahkan dalam penelitian pada Bab 3. Karena ada perubahan dari waktu ke waktu dalam tingkat kenyamanan dan ketidaknyamanan ini, sumbu ketiga yaitu waktu dapat ditambahkan ke dalam interaksi ini.

Penelitian doktoral ini menghasikan informasi dasar yang dapat digunakan dalam penelitian dimasa yang akan datang dengan sensor dan teknologi canggih yang memungkinkan peneliti dan produsen untuk mengumpulkan lebih banyak data manusia tanpa mengganggu peserta eksperimen (penumpang). Hal ini dapat berkontribusi untuk mengurangi masalah untuk secara terus-menerus meminta peserta eksperimen untuk menilai sendiri tingkat kenyamanan mereka. Dalam penelitian-penelitian selanjutnya, pengamatan melalui kamera dapat digunakan untuk mengatasi masalah ini. Analisis cerdas terkini dengan merekam gerak tanpa sadar manusia dan mempelajari parameter variabilitas denyut jantung cukup menjanjikan dan dapat dieksplor lebih jauh dengan adanya sensor-sensor terbaru. Hal ini memungkinkan cara baru untuk mengolah data-data yang dihasilkan. Ketidaknyamanan kedepannya mungkin dapat diukur dengan sensor tekanan di kursi, sedangkan kenyamanan dapat diukur dengan parameter variabilitas denyut jantung. Cara baru ini pada akhirnya membawa kita kepada hasil yang lebih dekat ke prediksi kenyamanan dan ketidaknyamanan, yang dapat dilakukan hanya dengan pengamatan.

Pada akhirnya, penelitian ini membuktikan bahwa entitas fisik dapat memprediksi kenyamanan, dan dengan mengamati interaksi serta merekam efek tubuh manusia seperti variabilitas denyut jantung juga dapat memprediksi kenyamanan. Selain itu, tersedia pilihan kuesioner untuk berbagai situasi yang dapat digunakan untuk memprediksi dan mencatat kenyamanan. Desainer juga dapat menggunakan metode ini untuk menciptakan interior pesawat terbang yang lebih baik secara fungsional dengan tingkat kenyamanan penumpang yang lebih tinggi.

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Reading Guide

Nomenclature

2D	Two dimensions
3D	Three dimensions
ANOVA	Analysis of Variance
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
BDI-II	Beck Depression Inventory
C	Experienced comfort, discomfort or nothing
CAN	Central autonomic network
CP-50	Category Particioning 50
CR-10	Borg's category ratio-scale 10
CR-100	Borg's category ratio-scale 100
CSI	Cardiac Sympathetic Index
CVI	Cardiac Vagal Index
DINED	Anthropometric data in design by Delft University of Technology
EEG	Electroencephalography
FAA	Federal Aviation Administration
FCC	Full-service carrier
GRS	Graphical rating scale
GWBS	The General Well-Being Schedule
H	Physical effect in the human body
HF	High frequency of the heart rate
HF norm	Normalized high frequency of the heart rate
HR	Heart rate
HRV	Heart rate variability
I	Interaction between human and environment
ISO	International Organization for Standardization
LCC	Low-cost carriers
LF	Low frequency of the heart rate
LF norm	Normalized LF
LF/HF Ratio	Ratio of LF/HF
LPD	Local Perceived Discomfort
MDBF	Multidimensional Mood State Questionnaire.
Mean HR	Mean heart-rate
Mean NN	Mean normal-to-normal interval
NRS	Numerical Rating Scale
P	Perceived by the human
P5	Percentile 5 of Human Anthropometric Data
P95	Percentile 95 of Human Anthropometric Data
PASAT	Paced Auditory Serial Addition Task

PE	Perceived effects
PhD	Doctor of Philosophy degree
PMR	Progressive muscle relaxation
pNN10	Proportion of number of interval differences of successive RR-intervals greater than 10 ms
pNN20	Proportion of number of interval differences of successive RR-intervals greater than 20 ms
pNN25	Proportion of number of interval differences of successive RR-intervals greater than 25 ms
pNN40	Proportion of number of interval differences of successive RR-intervals greater than 40 ms
pNN50	Proportion of number of interval differences of successive RR-intervals greater than 50 ms
pNNxx	Proportion of number of interval differences of successive RR-intervals greater than a certain number
PNS	parasympathetic nervous system
PSQ	Perceived Stress Questionnaire
RMANOVA	Repeated Measures Analysis of Variance
RMSSD	Root mean square of successive NN interval differences
RR	Inter-beat interval of the heart rate
RQ	Research question
SAGAT	Situation awareness global assessment technique
SD1	Standard deviation of projection of the Poincaré plot on the line perpendicular to the line of identity
SD2	Standard deviation of the projection of the Poincaré plot along the line of identity
SD3	Standard deviation of the 3rd axis used in 3D Poincaré plot
SD2/SD1 Ratio	Ratio of SD2/SD1
SDNN	Standard deviation of the time interval between successive normal heart beats
SDSD	Standard deviation of differences between adjacent normal to normal intervals
SMFs	Small movements and fidgets
STAI	Psychological stress using State-Trait Anxiety Inventory
STFT	Short-time Fourier transform
TRIM-T	Trimmel's Index of Trait Moods
TSST	Trier Social Stress Test
TTOL	Taxi, take off, and landing
VAS	Visual analogue scale
VDS	Verbal descriptor scale
WTP	Willingness to Pay

CHAPTER 1

Introduction

Overview

In 1903 the Wright Brothers made the first successful flight. Since then, airplanes continued to improve with new designs and technology enabling people to travel easily. Nowadays, airplanes have been known to be the quickest long-distance travel transportation mode. People fly all over the world for both work and leisure. Flying economy with a commercial airline is the cheapest and most accessible mode for many travellers. These airlines have been providing different cabin interiors to attract even more travellers on board at a competitive price. Having economy class seats with minimum space would allow airlines to cram more passengers into airplanes.

Have you ever sat in a cramped airplane? Sitting shoulder-to-shoulder with restricted legroom might not be a comfortable experience while flying in an airplane (see Figure 1). An earlier study by Richards et al. [1] in 1978 found that seat comfort is the most contributing factor to the willingness to fly again. Comfort is still found important 40 years later, where recent studies still show there is a correlation with comfort and willingness to fly again [2–5]. Even though the COVID-19 pandemic has crippled global air travel with many travel restrictions, people are still interested and willing to travel again when they are allowed to [6].

Figure 1. Sitting cramped in economy class seats

Many factors that influence passenger comfort. Human anthropometry is found to be one of the most important factors [7]. These body dimensions are an important aspect to consider in designing for large populations, e.g. having both the small (P5) and large (P95) people fit in the airplane seat [8]. The seat width and legroom are found to play a big role in designing comfortable aircraft seats [1]. Vink [9] found that providing legroom enables passengers to stretch legs which results in a changing body posture as a way to prevent discomfort. Many studies recommended an increase in the distance between rows of seats (pitch) and seat width based on the change of human anthropometry [2, 10–12].

However, increasing pitch and width is probably not the best for airline revenues. Therefore, other solutions are studied as well. Modern material advancements have enabled designers to make lightweight seats with a thin backrest for aircraft [13–17]. These new designs would allow passengers to have more space while sitting in an airplane. But this advancement could also mean that airlines allow more people in an aircraft. As the number of passengers grew year by year [18], it is an option for airlines to increase the number of passengers on board by placing the rows closer to each other [19]. By adding more people to a flight, the ticket prices could be lower as many passengers seek comfort at a low price [20, 21].

This results in a dilemma of whether to increase the seat size for passenger comfort or to increase the number of passengers on-board to lower the ticket price. There is not a clear answer to this dilemma. Some passengers would seek the most comfortable seat at the same price [22] and some are even willing to pay a higher fare for comfort in the cabin [23]. Finding the optimum between price and comfort might be difficult for airlines. This PhD research can be helpful to airlines and manufacturers to find the optimum as background information is gathered about the level of comfort experienced by passengers in different seat sizes.

Aircraft Interior Design

Many studies have tried to improve the aircraft interior. Some studies focus on noise and vibration [24–26] and other studies look at factors influencing passenger comfort [27–34]. De Crescenzio et al. [35] designed a virtual reality cabin for regional aircraft interiors, while Savian [36] focused on the general layout of the cabin. Seats are also a focus in aircraft interior studies. Zhao et al. [37] measured seat pressure distribution for improving seat comfort, Hiemstra-van Mastrigt et al. [15] used 3D scanning to design a seat to fit the body contour, Bouwens et al. [38] implemented an in-seat exercise, Fisher [39] and Rickenbacher and Freyenmuth [40] used the pneumatic technology to adapt seat shape, while Beheshti et al. [41] improved the crash-worthiness of the aircraft seat.

There are studies available focusing on seat dimensions. For instance, one study found that there is a relationship between sitting discomfort and seat pitch, and that sitting discomfort also increases turnaround time [42]. Another study related seat pitch to passenger well-being, which was found to be psychologically driven through space experience [43]. Moerland [44] made a hypothetical model on the relationship between seat pitch, seat width and comfort. These improvements of aircraft seats could bring positive emotions to the passenger [45]. The goal of comfort in an aircraft interior design is not only achieved by experiencing comfort but also pleasure and expectations play a role [45].

In this study, experiments are conducted to gather background Information on how comfort can be achieved, which contribute to a pleasant experience. To create a framework for the studies, comfort models described in the literature will be discussed.

Comfort Definitions & Models

The feeling of comfort and discomfort is not a false dilemma enabling people to experience both situations at the same time [46]. Vink and Hallbeck [47] defined comfort as "a pleasant state or relaxed feeling of a human being in reaction to its environment", while discomfort is "an unpleasant state of the human body in reaction to its physical environment".

Early comfort research believed that comfort and discomfort were the exact opposites, where the discomfort and comfort could not occur simultaneously [48]. Helander and Zhang [46] influenced the comfort research field by distinguishing comfort and discomfort based on questioning seat users. Based on questionnaires by Zhang et al. [49] and Helander and Zhang [46] discomfort is related to physical characteristics, e.g., posture, stiffness and fatigue. The absence of discomfort does not automatically result in comfort. Comfort is driven by well-being and plushness, and will be felt when the experience is higher than the expectation (Figure 2). This model was further developed by Vink and Hallbeck [47]. They made an addition by which it is possible to predict comfort or discomfort (Figure 3). In their model, a process is shown starting with the interaction between human and the product until the final step of feeling either comfort, discomfort or nothing by the human.

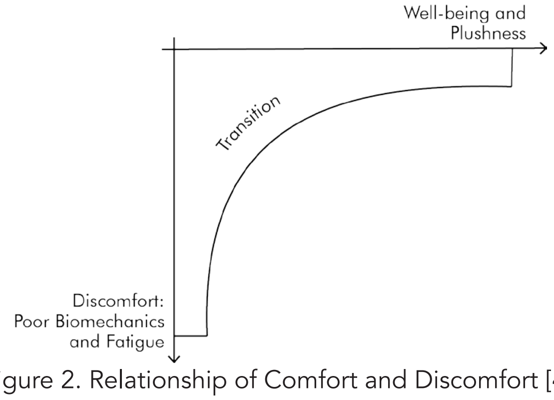

Figure 2. Relationship of Comfort and Discomfort [49]

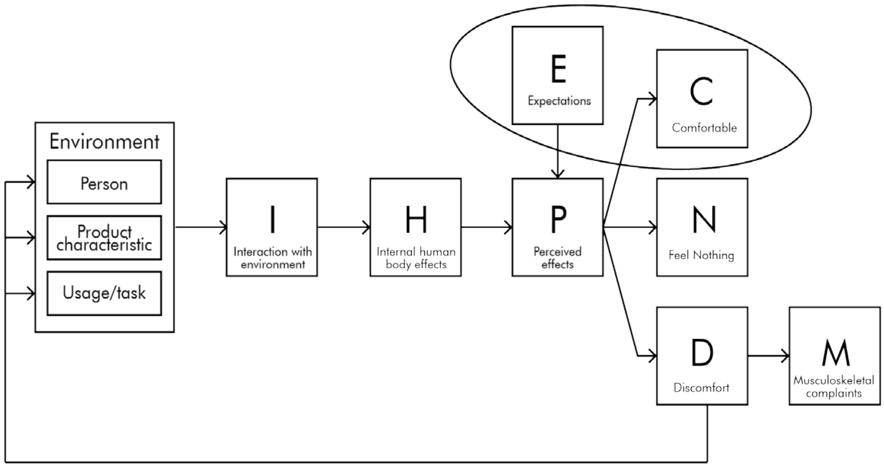

Figure 3. Comfort Prediction Model [47]

The model of Vink and Hallbeck (Fig. 2, [48]) is applied in many comfort research. Naddeo et al. [51] modified this model for postural comfort even further in detail.

Research Focus and Approach

According to the model of Vink and Hallbeck [47], the human in combination with the physical entities (PE) results in an interaction (I) between the human and the physical entity, which results in a physical effect in the human body (H), which is perceived (P) by the human and then comfort or discomfort is experienced (C) or nothing at all. There is a gap in knowledge as not all elements of the model have been studied. In this PhD research, experiments were conducted to gather knowledge on all elements of the model and contribute to a deeper understanding of the relationships. Additionally, methods to study the different elements will be applied and evaluated.

The aim of this research is to understand how to predict comfort (C) by looking at the physical entities (PE), its interaction (I) with the human, the human body effects (H) and perceived effects (P). The application area of the model is the aircraft interior. Therefore, the research objective of this PhD thesis is:

To increase aircraft passengers' comfort by creating knowledge on those physical entities that predict comfort

As this is a broad scope, the research objective is narrowed down into three phases and six research questions. This thesis is structured according to these phases. The first phase focuses on physical entities (PE), then the interaction (I) is studied, followed by human body effects (H) and finally perceived effects (P) is studied (see Figure 4). In this research, the links are studied, but also methods, sometimes new ones, to measure the elements are applied and evaluated.

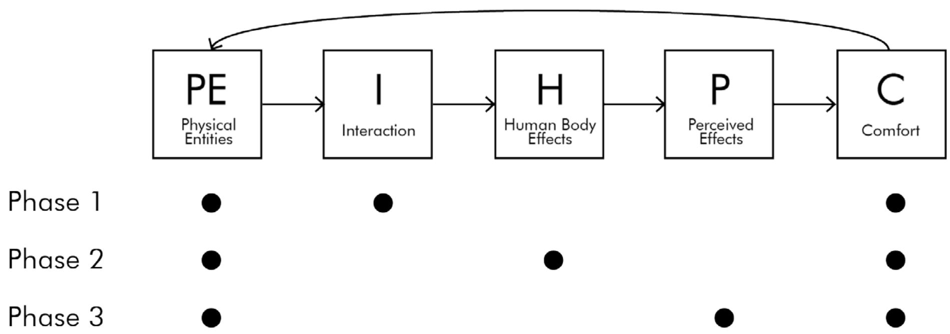

Figure 4. Physical entities that predict psychological comfort

Phase 1: Different seat space of an aircraft (PE) will be explored focusing on interaction (I) between different people and the interior, resulting in comfort (C)

1. What is the relationship between seat pitch and comfort, and what are the roles of different factors in this process, such as space experience and anthropometrics?
2. What is the relationship between space experience and human anthropometrics at different seat pitches?
3. What is the effect of widening a seat from 17" to 18" on comfort? And is the effect of widening the seat comparable to the increase of a certain pitch?

Phase 2: The results of phase 1 will be further explored by measuring the human body effects (H) (e.g. heart rate variability (HRV)) leading to comfort.

4. Does comfort and discomfort change over time regarding different types of seats? Are there any relationships between various metrics of HRV and the feeling of comfort/discomfort of passengers? And if so, which parameters of HRV can be used in predicting comfort/discomfort over time?

Phase 3: This phase will focus on exploring the questionnaires as a methodology to measure perceived comfort (P).

5. Which questionnaires can be included in the Preferred Comfort Questionnaires (PCQ) list for product design?

Design implications: An application of the results of the study of physical entities (PE) leading to comfort (C) will be explored.

6. Which seat configuration is more preferred by experts for the premium economy? And which choice is more beneficial?

Embedding in the Institution

This PhD project was conducted at the Faculty of Industrial Design Engineering, Delft University of Technology (TU Delft). It is part of the societal challenge "Mobility" and the disciplinary perspective "People" of research themes in the faculty.

Thesis Outline

The structure of this thesis (Figure 5) follows the aforementioned research questions. It consists of 6 chapters: Chapter 1 (this chapter) introduces the societal relevance and the framework of the research.

Chapter 2 focuses on the physical entities of the airplane and anthropometrics and the effect on comfort perception. Two studies are conducted based on varying the pitch and the width of an airplane seat. In the first study, 294 participants experienced economy class seats in a Boeing 737 with 28-inch, 30-inch, 32-inch and 34-inch seat pitches (PE of the airplane). Anthropometric measurements of the participants were taken as well (physical characteristics of the humans) and interaction (I) was studied by linking the seat dimensions to the anthropometrics. Participants completed a questionnaire on comfort (C) and space experience. The second study recruited 311 participants and compared the 17-inch wide and 18-inch wide seat (PE) and also recorded their anthropometric data and its interaction (I) with space experience and comfort (C).

Chapter 3 explores this interaction further, by studying the resulting human body effects leading to comfort and discomfort. A study was designed with 16 participants on two different seat pitches (28 inches and 30 inches) and two different seat widths (17 inches and 18 inches) (PE). Participants sat continuously in an aircraft seat for 2-hours while doing different tasks (I). Their heart rate was monitored constantly and parameters of HRV were analysed (H). Comfort and discomfort were recorded every 15 minutes by questionnaires to investigate the change of comfort (C) over time.

Chapter 4 is an explanation of questionnaires to measure perceived comfort (P) in different phases of the product design process. The aim of this study is to create a list of PCQ: Preferred Comfort Questionnaires for product design to help researchers in the selection of questionnaires for comfort research (C). Fifteen questionnaires that are often used in comfort research for product design were selected as candidate questionnaires. Fifty-five researchers and practitioners working in the field of comfort joined together in a workshop to rate these questionnaires individually as well as rank them in groups based on their experience.

Chapter 5 is an application of the research, studied by examining layouts made by experts in the field. The results of the previous chapters are presented to aircraft interior experts and preferred layouts (PE) by these experts would be analysed regarding different criteria. Eighty-eight experts in the field of aircraft interiors were invited to make a floor plan of a part of a Boeing 777 aircraft where comfort (C) was one of the main goals. Participants worked in groups of 3 and are given the freedom to design a section of the cabin between economy and first-class (5.87m wide and 3.7m long). The results of the experts were later compared to layouts produced by computational algorithms to evaluate the advantages of each method.

Chapter 6 discusses the outcome of the research project, reflects on other literature and presents a conclusion.

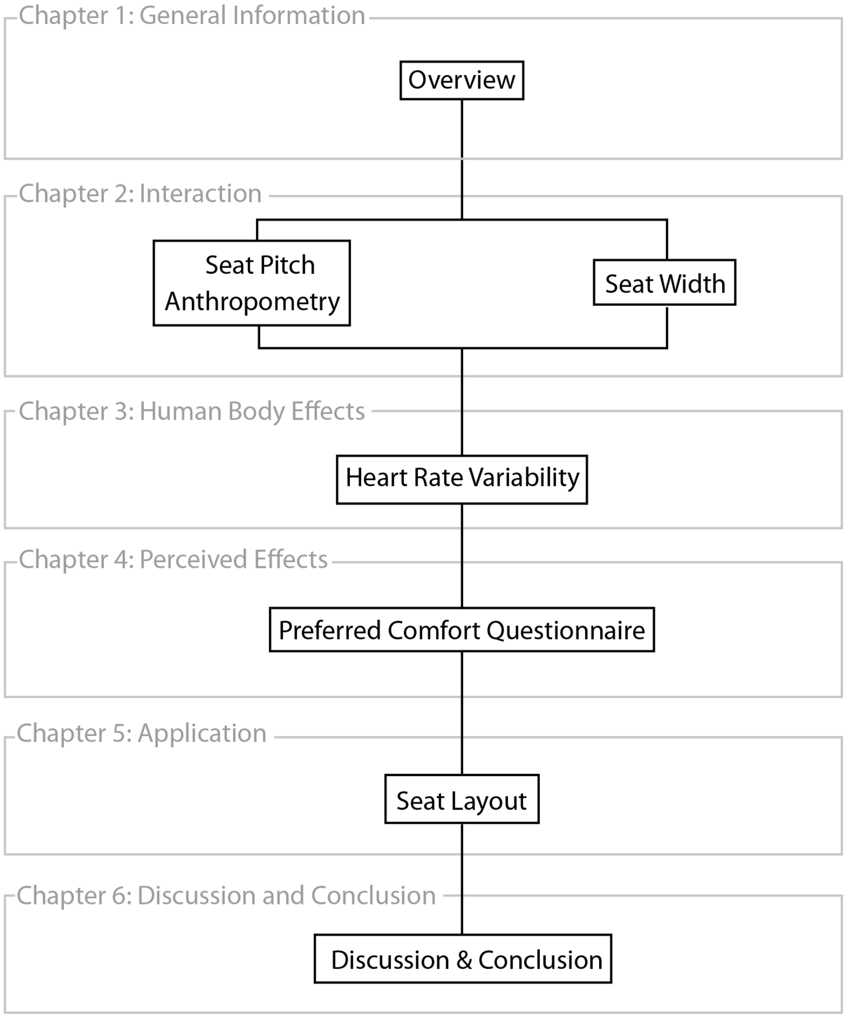

Figure 5. Chapter overview

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CHAPTER 2

Interaction

This chapter is based on:

Anjani S, Li W, Vink P, Ruiter I (2019) The Relationship of Space Experience and Human Anthropometric Sizes in Aircraft Seat Pitch. In: Bagnara S, Tartaglia R, Albolino S, et al (eds) Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018). Springer, Cham, Florence, Italy, pp 504–511

Anjani S, Li W, Ruiter IA, Vink P (2020) The effect of aircraft seat pitch on comfort. Appl Ergon 88. https://doi.org/10.1016/j.apergo.2020.103132

Anjani S, Song Y, Hou T, Ruiter IA, Vink P (2021) The effect of 17” and 18” aircraft seat width on comfort. Int J Ind Ergon 82. https://doi.org/10.1016/j.ergon.2021.103097

The relationship of space experience and human anthropometric sizes in aircraft seat pitch

Abstract

This study explores the relationship between space experience and human anthropometric sizes in different aircraft seat pitch. 294 participants experienced economy class seats in a Boeing 737 with 28 inches, 30 inches, 32 inches and 34 inches pitches for 10 minutes each. The sizes taken were: stature, sitting height, eye height seated, buttock-knee length and popliteal height sitting with shoes. A space experience questionnaire was completed by the 294 participants while sitting in the seat after the 10-minute period given to explore the seat. The results show that passengers with a higher popliteal height, a longer buttock-knee depth, a higher eye height sitting and a higher sitting height show more discomfort with a reduced pitch then shorter passengers. Eye height did not correlate as good with space perception as was expected.

Keywords: Seat Pitch, Comfort, Discomfort, Space Experience, Anthropometric measurements.

Introduction

People travel in many different ways. The choice of transportation modes differs among individuals, depending on their wishes and needs. Comfort is one of the important considerations in choosing a certain transportation mode [1] and it also has a strong correlation with repetitive choices [2].

Vink, Hallbeck [3] defined comfort as a pleasant state or relaxed feeling of a human being in reaction to its environment, while discomfort is an unpleasant state of the human body in reaction to its physical environment. This comfort perception is found in a slightly different form in Zhang et al. [4]'s model, where comfort is driven by well-being and plushness, while discomfort is due to poor biomechanics and tiredness (Figure 1). This study will use this definition. Vink and Hallbeck [3] further developed the model which is able to predict discomfort (Figure 2). The model presents how comfort is perceived as well as the factors which may contribute to comfort perception.

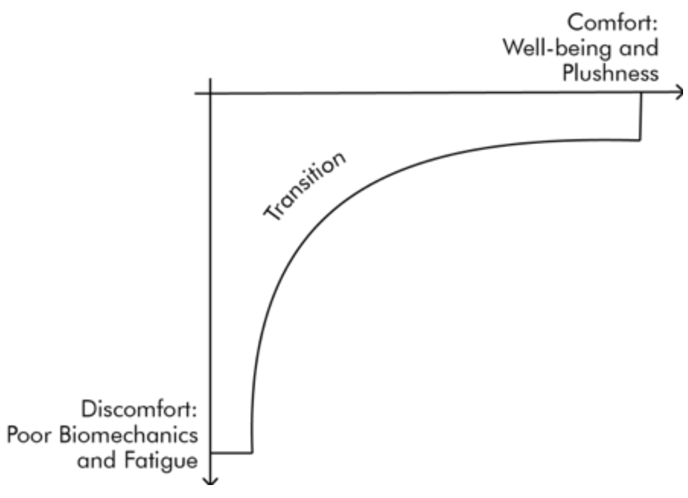

Figure 1. Comfort model by Zhang et al. [4]

This experiment focuses on the link of the environment to the interaction (I) with the environment (see Figure 2) which at the end of the model will result in either comfort, nothing, or discomfort [4]. Furthermore, this comfort and discomfort feeling could also be driven by psychological [5], physiological [6] or emotional influences [7]. This study only focuses on the psychological and physiological relationship with (dis)comfort.

Legroom is found to be a major element contributing to comfort when sitting in an aircraft. Vink [8] found that providing legroom enables passengers to stretch legs which results in a changing body posture as a way to prevent discomfort. Curtis et al. [9] also found that legroom is an important factor for frequent flyers' level of satisfaction. Vink et al. [10] showed that legroom has a high correlation with comfort. On the contrary, Blok et al. [11] found that the knee space which is also related to legroom was the lowest-rated item. In the last 30 years, this legroom decreased as the distance of the rows have decreased 2 to 5 inches [12].

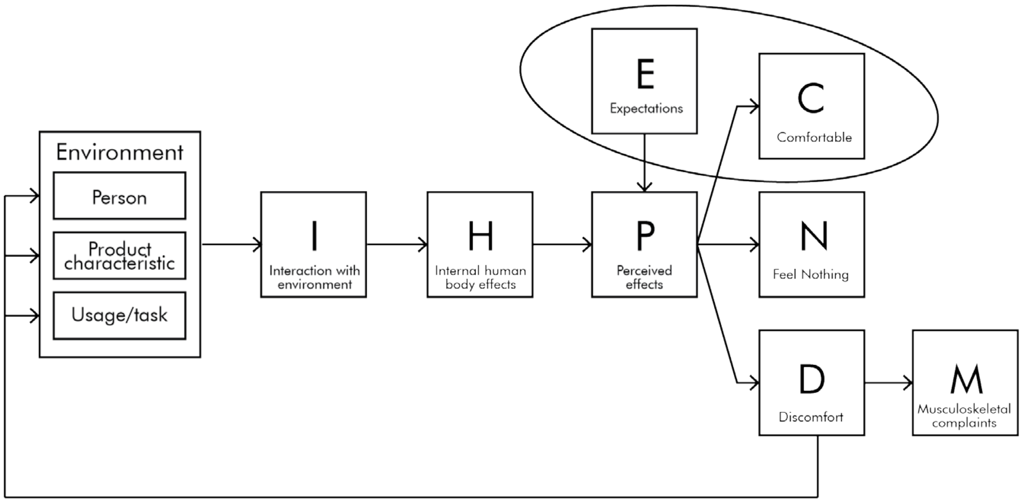

Figure 2. Comfort Prediction Model by Vink, Hallbeck [3]

Legroom is influenced by the distance between rows of the seats which is known as seat pitch, measured from a point in a seat to the exact same point of the seat in front or behind. Today's seat pitch size vary from 28 inches to 38 inches for economy class flights [13].

Some studies are done on the relationship between seat pitch and comfort. Anjani et al. [14] found a significant relationship between seat pitch and comfort as well as discomfort. A different study found that there is a relationship between sitting discomfort and seat pitch, and that sitting discomfort also increases through time [15]. Kremser et al. [16] found an influence of seat pitch on passenger well-being which was found to be psychologically driven through space experience. A different study was done by Menegon et al. [17] who also looked at psychological aspects of aircraft seat comfort by using item response theory. Menegon et al. [17] found that comfort tends to increase when aspects of the aircraft seat are improved and positive emotions are elicited. This maximum comfort is achieved when pleasure is experienced and expectations are exceeded.

There are indications that the mismatch of human body dimensions with the environment is the main cause of a poor interaction which generates changes in the human body and results in physiological (dis)comfort perception. Kremser et al. [16] found relationships between human anthropometry and well-being at different seat pitches, indicating the existence of this relationship as well. This study explores the relationship between space experience [16, 17] and human anthropometry [18] at different seat pitches.

Methods

Participants and Anthropometric Measurements

Two hundred and ninety-four participants (135 males and 159 females; aged 17-23 years) were measured according to the DINED method [18]. The sizes taken were: stature, sitting height, eye height seated, buttock-knee length and popliteal height sitting with shoes on. The popliteal height included shoes because participants were asked to sit in the aircraft seat with their shoes on. This research was conducted in autumn so some participants wore thin jackets. All thick coats and baggage were asked to be put in the overhead compartment to minimize space influence. The popliteal height sitting with shoes were measured on the day of the experiment ensuring the measurements were consistent with the shoes worn that day. The other measurements were done in sessions after the experiment.

Experiment Setup

To study the relationship between experience, seat pitch and anthropometrics, eight rows of economy class seats (see Figure 3; Table 1) in a Boeing 737 fuselage were used with 28 inches, 30 inches, 32 inches and 34 inches seat pitch. The pitch sizes used in this experiment were based on the sizes currently often seen for economy class flights (28 inches to 38 inches) [13]. The even numbers were selected enabling to match results to other references [14–16, 19]. Half of the setting was arranged to have the participants experience the pitch size from small to large, the other half from large to small. This was done to eliminate the order effect. The changes were small, but participants could refer it to the previous experience and in theory, this would be recognisable since human sensors record differences better than absolute values [20]. Participants were not allowed to recline their seats since this might influence the situation of the participants behind them.

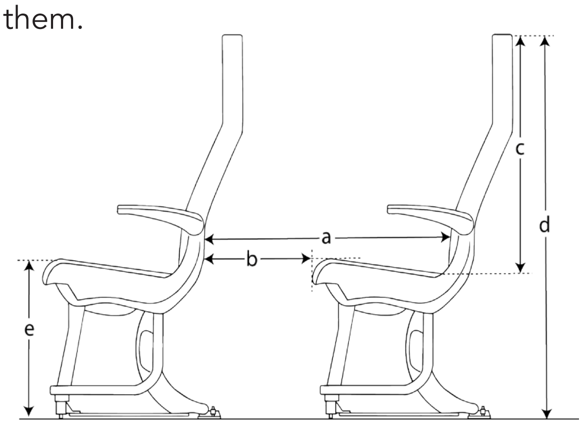

Figure 3. Seats used in this study

Table 1. Seat dimensions

Dimensions	28″	30″	32″	34″
a	64 cm	69 cm	74 cm	79 cm
b	20 cm	25 cm	30 cm	35 cm
c		71 cm		
d		111 cm		
e		44 cm		

Participants were asked to sit in 4 different seat settings for 10 minutes each without any instructions on what to do while sitting. All seats were occupied so all participants had a neighbour. As it were students from the same faculty and year most were acquainted with each other. After 10 minutes of sitting participants were asked to complete an online questionnaire while remain seated. After completing the questionnaire participants were allowed to stand-up and move to a different pitch size. The participants were instructed to sit in the same seat position in all 4 different pitches, e.g. the person sitting in an aisle seat would remain in an aisle seat for all seat pitches. The seats used were a 3-seat configuration for a single-aisle aircraft.

Space experience evaluation

Eight statements (see Table 2) were used to evaluate the space experience using a 9-scale Likert with half using positive descriptors leading to comfort and the other half using negative descriptors leading to discomfort [21]. These descriptors were based on the study of Zhang et al [4] where some words are related to comfort and others to discomfort. Q1 until Q4 are made with negative descriptors and Q5 until Q8 with positive descriptors. These statements were psychological questions on space perception related to seat pitch [16, 17]. A Spearman-rank correlation was done to results using SPSS version 24.

Table 2. Space experience statements.

Statement number	Statement
Q1	I feel restricted by the distance of the seating rows
Q2	I feel like sitting in front of a wall
Q3	I feel lost because the distance of the seating rows
Q4	I feel stressed out because of the distance of the seating rows
Q5	I was able to stretch my legs without difficulty
Q6	The backrest was able to support my needs
Q7	There was enough room to get in and out of the seat
Q8	I can change easily from one sitting posture to another

Results & Discussion

Anthropometric Measurements

All participants in this study were Dutch students. Table 3 shows that most measurements were close to Dutch reference data. The anthropometric measurements that were not correctly measured were excluded from the results, for example when the eye height seated was longer than the sitting height.

Table 3. Average anthropometric measurements and reference data (mm).

Mean	Observations in this study	Male database [18]	Female database [18]
Stature	1762	1821	1698
Sitting height	906	949	898
Eye height seated	801	840	787
Buttock to knee	596	634	600
Popliteal Height with Shoes	466	-	-

Space Experience Evaluation in Different Pitch Sizes

The results of the space experience questionnaires are shown in Table 4. It was found that the positive descriptors of space experience (Q5-Q8) increase with the increased pitch size, with the exception of Q6, while the negative (Q1-Q4) did decrease with the increase of pitch size. Statement Q6 which was "The backrest was able to support my needs" was found to be higher in the 30" seat pitch than 32". This result could be influenced by not allowing the participants to recline the seat during the test. All results of these statements were found significant (Spearman-rank correlation, $p<0.01$).

Table 4. Results of space experience statements

Statement	28"		30"		32"		34"		r_s
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Q1	6.92	2.00	4.57	1.86	3.18	1.53	1.97	1.51	-.718**
Q2	6.50	2.08	4.49	1.79	3.51	1.66	2.23	1.41	-.652**
Q3	3.48	2.32	2.74	1.53	2.37	1.44	2.15	1.46	-.233**
Q4	5.52	2.15	3.68	1.81	2.80	1.54	1.91	1.23	-.594**
Q5	3.74	2.56	5.37	2.25	6.52	2.33	7.87	2.06	.568**
Q6	5.53	1.90	5.79	1.58	5.55	1.87	6.43	1.71	.162**
Q7	3.60	1.75	5.25	1.71	5.90	1.78	7.48	1.62	.632**
Q8	3.69	2.06	5.37	1.77	6.16	1.80	7.42	1.54	.597**

**. Correlation is significant at the 0.01 level (2-tailed).

Relationship of Anthropometric Measurement and Space Experience.

The relationship between the anthropometric measurements and space experience is shown in Table 5. It was found that the popliteal height with shoes and buttock to knee length were found significant to all space experience statements. Q1, Q4, Q5, and Q8 were also found correlating strongly with all anthropometric measurements. So, the anthropometric measurements indicating physiological comfort highly correlated with space experience, which could indicate that these measurements are a good predictor of space experience leading to psychological comfort.

Kremser et al. [16] and Moerland [19] presented that the buttock to knee measurement strongly correlates with seat pitch and (dis)comfort, in this case, using space experience statements. In our study, the thickness of the backrests was equal. Seat pitch is not always directly related to legroom as a thicker backrest creates less legroom [22]. The new economy class seats usually have a thinner backrest for this reason. All statements were also found significant for eye height seated, though some were not strong, which is also in-line with other findings [16]. Sitting height which was assumed to have an influence psychologically in space experience only had correlations in Q1, Q4, Q5 and Q8 while all other measurements were also correlated. This might indicate that sitting height is not a predictor of space experience. The two highest correlations were found between Q5 'I was able to stretch my legs without difficulty' and popliteal height with shoes.' (This makes sense as the longer the lower leg the more difficult it is to stretch the legs) and Q1 'I feel restricted by the distance of the seating rows' and popliteal height with shoes. As the back of the seat in front of the passenger comes closer at a higher level, it also makes sense that occupants with longer lower legs feel more restricted. Some values were not significant: sitting height did not have a strong relationship with Q2, Q3, Q6 and Q7, which also makes sense as buttock-knee distance has more influence on space experience than the height of the head as there are no physical restrictions above the head.

Table 5. Relationship of Anthropometric Measurements and Space Experience

Statement	Sitting height	Eye height seated	Buttock to knee	Popliteal height with shoes
Q1	-.192**	-.196**	-.205**	-.263**
Q2	-.051	-.126*	-.184**	-.167**
Q3	-.055	-.122*	-.153**	-.139**
Q4	-.159**	-.185**	-.177**	-.168**
Q5	-.192**	-.196**	-.205**	-.263**
Q6	-.051	-.126*	-.184**	-.167**
Q7	-.055	-.122*	-.153**	-.139**
Q8	-.159**	-.185**	-.177**	-.168**

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

The limitation of this study is that the population is young and only from one area of the globe and the duration of the seating was 10 minutes, while in a real flight the duration is longer. It is expected that the effects will be larger for longer flights as other studies show that discomfort increases over time (e.g. Smulders [23]). The anthropometric data are not completely independent as larger persons could have larger lower and upper legs. This means that we are not sure whether the effect can be only contributed to buttock to knee length or popliteal height.

Conclusion

A relationship between space experience and human anthropometric sizes in aircraft has been established. Passengers with a higher popliteal height and a longer buttock-knee depth show more negative results in space experience with reduced pitch compared to shorter passengers. Therefore, the taller the passenger, the larger the problems could be expected with low seat pitches, physiological as well as psychological.

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The effect of aircraft seat pitch on comfort

Abstract

This study explores the relationship between seat pitch and comfort, and the influencing factors, like space experience and anthropometric measurements. Two hundred ninety-four participants experienced economy class seats in a Boeing 737 with 28-inch, 30-inch, 32-inch and 34-inch seat pitches. Anthropometric measurements of the participants were measured. Participants completed a questionnaire on comfort (10-scale), discomfort (CP-50) and space experience and the results were analysed using SPSS 25. This study showed a significant relationship between seat pitch and comfort as well as discomfort. Additionally, it was found that the mean rank of the discomfort of each pitch size for the middle seat was higher than the window and aisle seat, though seat pitch did affect the (dis)comfort more compared with seat location. It was also found that anthropometric sizes significantly affect the (dis)comfort on smaller pitch sizes, and all space experience statements had a correlation to the pitch sizes.

Keywords: Seat pitch, Comfort, Discomfort, Space experience, Anthropometric measurements

Introduction

Approximately 3.6 billion passengers flew in 2016. This number continues to increase through the years [1]. To fulfil this emerging market, airlines are increasing the number of rows in an aircraft by placing them closer to each other. Due to this increasing demand, the distance of the rows has decreased 2 to 5 inches through the last 30 years [2]. In 2015, Flyers' Rights, an airline consumer organisation, filed a petition to the Federal Aviation Administration (FAA) Organization on the "Case of the Incredible Shrinking Airline Seat" regarding this issue [3].

Today's seat pitch sizes vary from 28 inches to 38 inches for economy class flights [4]. The seat pitch itself is measured from a point in a seat to the exact same point of the seat in-front/behind it [5]. The arrangement of the seat pitch will affect the legroom or knee space. Legroom, as a result of seating row arrangements, is an important factor in passenger comfort [6]. Minimal legroom is calculated by adding 2.5 cm to the 95th or 99th percentile of the buttock-to-knee length of the population [7]. Providing sufficient legroom enables passengers to stretch legs which result in a changing body posture as a way to prevent discomfort [5]. Research also shows that legroom is an important factor for frequent flyers' level of satisfaction. Vink et al. [6] also showed that legroom (r=0.718) has a high correlation with comfort. The same study also found a strong correlation (r=0.730) between comfort and "fly again with the same airlines." Despite this importance, Blok et al. [8] found after studying the 291 passengers' trip reports and interviewing 152 subjects that the knee space is the lowest rating item, followed by the personal space and seat width, especially knee space was seen as a problem by taller passengers for the long-haul flight.

Some research indicates that comfort is related to pitch. Li et al. [9] found that there is a relationship between seat pitch and sitting comfort. Moerland [10] made a hypothetical model on the relationship of seat pitch, seat width and comfort. Kremser et al. [11] found the influence of seat pitch to passenger well-being. "Space experience" a psychological factor on comfort related to seat distances was found to be related to human anthropometry [12]. There are different causes of comfort, such as psychological [13], physiological [14, 15] and emotional causes [16].

There are indications that comfort and discomfort are two different entities rather than extremes of one scale [17]. Zhang et al. [18] made a model where comfort is driven by well-being and plushness, while discomfort comes from poor biomechanics and tiredness. Vink et al. [19] also defined comfort as a "feeling and discomfort as a state of the human body". Discomfort is related to physical feelings of pain, soreness, and so on. Comfort is established by the feeling of relaxation and well-being. Both comfort and discomfort were included in this study.

The aim of this study is to investigate the relationship between seat pitch and comfort, and its influencing factors, such as space experience and anthropometrics. The first hypothesis of this study is that comfort is correlated significantly with pitch size based on the hypothetical model of Moerland [10]. Second, that space experience and anthropometrics influence comfort. Negative space experience statements are assumed to lead to discomfort, while positive statements lead to comfort [17]. A correlation is also assumed between buttock-to-knee length and discomfort, as the minimum seat is based on the buttock-to-knee length of the population [7]. The correlation between eye-height seated and comfort is also tested as comfort is derived from psychological well-being which is affected by visual perception [18, 20].

Method

Participants

To study this relationship, 294 participants (135 males, 159 females, aged 17-23 years) sat on the tested aircraft seats in 8 groups of approximately 45 participants. The participants were first-year students studying at the Delft University of Technology. All participants were asymptomatic for low back pain and did not have any musculoskeletal injury. Before the experiment, all participants were asked to give informed consent that we were allowed to use the data in research. Participants who did not give consent were excluded from the data. Each participant took approximately 2 hours to complete the study.

Protocol

This study was conducted in a Boeing 737 airplane located at the campus of the Delft University of Technology. It had a 3-3 configuration, the seat setup in the first nine rows is shown in Figure 1. All seats have the same form with different pitches. Four pitch sizes were chosen: 28 inches, 30 inches, 32 inches and 34 inches. The seats used were economy class seats (for dimensions see Figure 2). The hip-to-knee space (a) is recorded horizontally 10 cm above the seat pan. During the experiment, the seat on the first row was not allowed to be occupied, since the pitch could not be controlled.

Sizes of the body parts were measured according to the DINED method [21]. The sizes taken were: stature, sitting height, eye height seated, buttock-knee length and popliteal height sitting with shoes. These sizes were taken as Kremser et al. [11] found that eye height seated and buttock-to-knee was related to comfort. Stature, sitting height, and popliteal height seated were added to find other possible correlations. These measurements were added to find possible seat design solutions based on anthropometry.

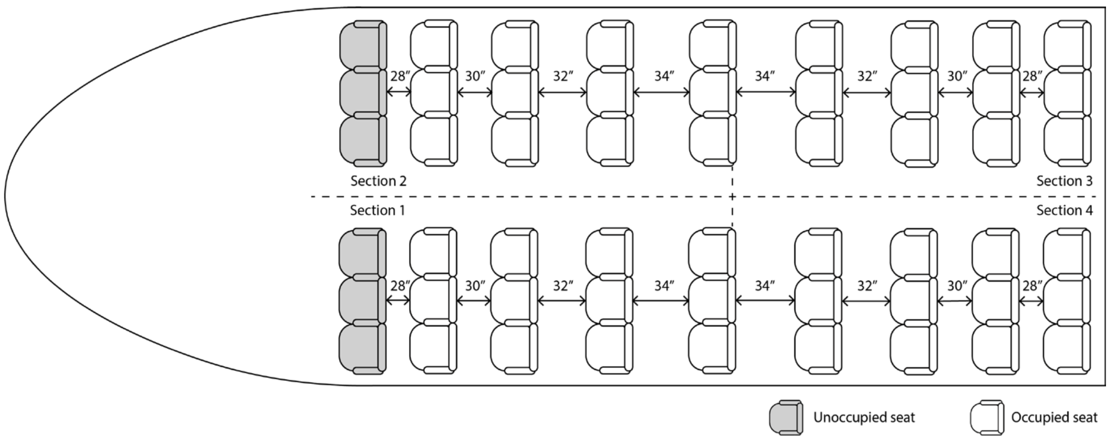
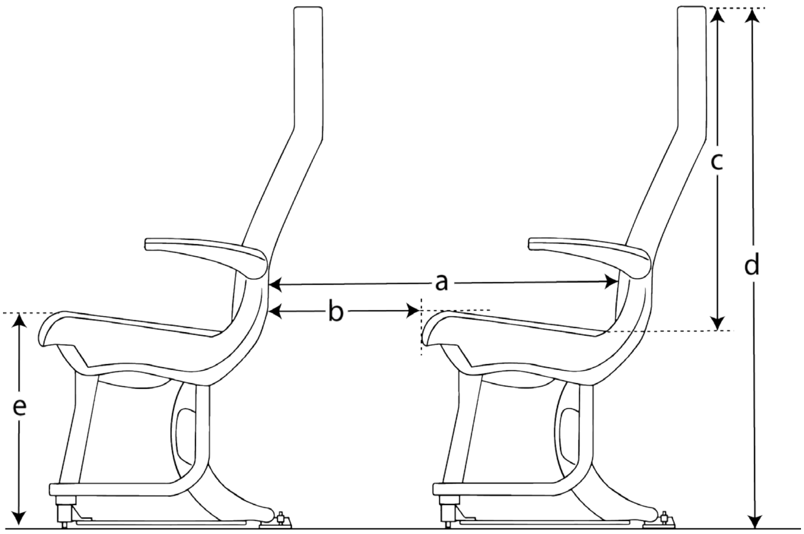


Figure 1. Seat layout in the test aircraft.

Before the participants entered the aircraft, they were given a verbal explanation of the research protocol. Each participant was given a number, and all data were coupled to that number. Every group of participants needed to finish four rounds in the experiment to enable a within-subject design, and every round lasted 10 minutes. When they first boarded the airplane, they can freely choose the seat from the second row to the ninth row. However, if a participant chose a middle, aisle or window seat, they had to take the same seat in the next rounds to prevent the effect of the position in the row. For each round, they were instructed to sit down for 10 minutes and complete the questionnaire after 10 minutes sitting while still sitting in the seat. The questionnaire was an online version to be completed using the smartphone, and participants without smartphones were given papers. Participants were allowed to talk to each other and to choose their position freely. They were not allowed to use the tray table and not allowed to recline their seats. The seats were divided into four sections to ease participant rotation (Figure 1). When a round is finished, participants move to the seat directly in front of them. When they reach the front row of each section, they would need to move to the last row of that section. This rotation order is made to eliminate the influence of order in this study.



Dimensions	28″	30″	32″	34″
a	64 cm	69 cm	74 cm	79 cm
b	20 cm	25 cm	30 cm	35 cm
c		71 cm		
d		111 cm		
e		44 cm		

Figure 2. Dimensions of Seat Used

Measuring methods

The questionnaire consists of three parts: a comfort scale, discomfort scale and space experience. To measure the discomfort level of each participant, a CP-50 scale (category partitioning scale) was included in each questionnaire. This subjective rating scale is found to be reliable and most valid for rating perceived discomfort on sitting and also was preferred more than other discomfort scales [22]. A 10-point comfort scale was used as well to make a comparison with the study of Moerland [10] possible (1=least comfortable, 10=most comfortable). Questionnaire items for space experience were gathered from studies of Kremser et al. [11], and Menegon et al. [23]. These statements on space experience shown in Table 1 [12] were included to learn more on the psychological effect of seat pitch on (dis)comfort. Only statements related to seat pitches are included in this study. Half of the statements were made using a positive descriptor leading to comfort and the other half using a negative descriptor leading to discomfort with a 9-scale Likert (from not at all to extremely) to enhance the intensity of each descriptor. This setting is based on a study of Helander and Zhang [17] which assumes that sitting comfort and discomfort are independent entities influenced by different factors.

All data were imported in SPSS version 25 and analysed with Spearman-rank correlation and Kruskal Wallis H test. Nonparametric statistical methods were chosen because comfort and discomfort data are not normally distributed [24]. Averages and standard deviation were calculated over participants. A Spearman's correlation was calculated between some body-measurements and (dis)comfort and between space experience, pitch and (dis)comfort. The significance of the correlation was calculated as well. Kruskal Wallis H tests were performed on comfort and discomfort between pitch sizes and also seat location to find whether there are significant effects. The results of the participants who have not completed the whole experiment or did not follow the order of the experiment were excluded from the analysis. The number of subjects for each analysis is stated with the results.

Table 1. Space Experience Statements [12]

Statement number	Statement
Q1	I feel restricted by the distance of the seating rows
Q2	I feel like sitting in front of a wall
Q3	I feel lost because the distance of the seating rows
Q4	I feel stressed out because of the distance of the seating rows
Q5	I was able to stretch my legs without difficulty
Q6	The backrest was able to support my needs
Q7	There was enough room to get in and out of the seat
Q8	I can change easily from one sitting posture to another

Results and Discussion

Comfort and discomfort on seat pitch size

The results of the questionnaires of 166 participants were used to calculate the relationship between pitch sizes, and overall comfort and discomfort. Figure 3 and Figure 4 shows the relationship of mean overall comfort and overall discomfort for the different pitches. This graph shows that there is a positive relationship between pitch size and the mean overall comfort and a negative relationship between overall discomfort and pitch sizes. The Spearman's correlation of pitch with overall comfort is found significant p=0.000 with an r=.719, and pitch with overall discomfort is also found significant p=0.000 with an r=-.525. A Kruskal Wallis H test was performed to see the effect of comfort and discomfort between pitch sizes. Both tests had significant results with H(3)=348.442, p=.000 for comfort and H(3)=184.74, p=.000 for discomfort.

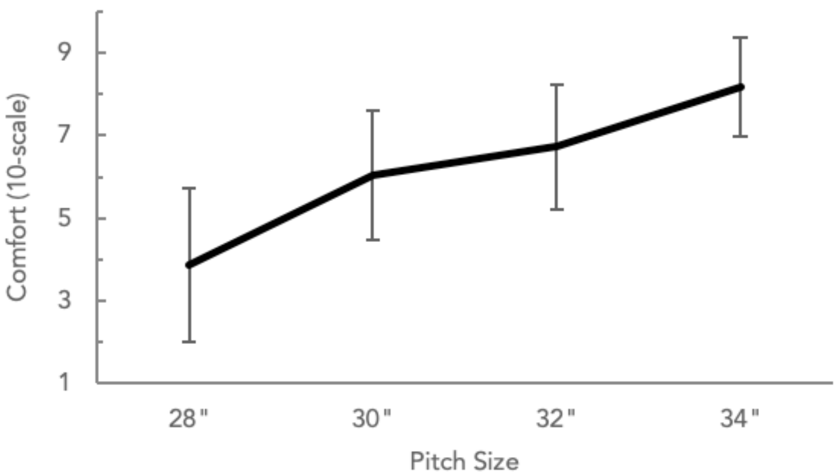


Figure 3. Mean Overall comfort (10-scale) by Pitch Sizes (inches)

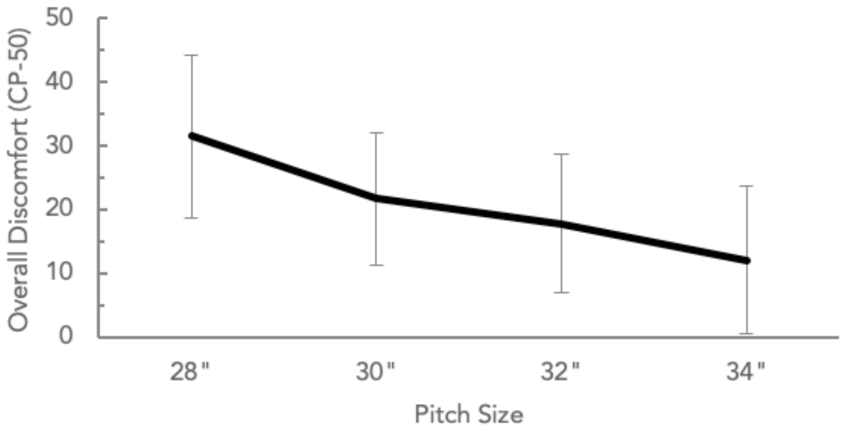
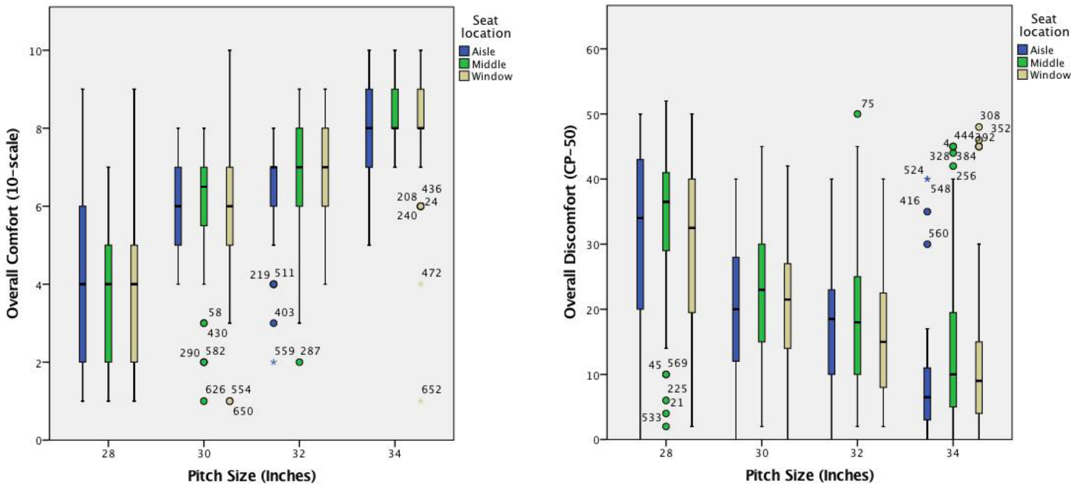


Figure 4. Mean Overall Discomfort (CP-50) by Pitch Sizes (inches)

All the seats in the rows tested were filled, so each participant had a neighbouring participant. Additionally, both comfort and discomfort data were analysed by the location of the seats (aisle, middle, window). Figure 5 shows the comfort and discomfort of different locations. A Kruskal-Wallis H test was performed to show the effect of seat location on comfort and discomfort. Results show that it was significant for discomfort between the different seat locations with H(2)=6.170, p=.046 with a mean rank score of 320.53 for the aisle, 357.09 for the middle and 317.46 for the window seat. However, results were not significant for comfort between different seat locations with H(2)=.382, p=.826 with mean rank score of 3207.12 for aisle, 330.37 for middle and 338.00 for window seat. The middle seat is found to have a higher mean overall discomfort in all pitches while the mean in comfort did not vary, though the effect on both comfort and discomfort on seat pitch was still higher than seat location.



(a) (b)

Figure 5. (a) Comfort and (b) Discomfort by Seat Location

Comfort and discomfort on anthropometric measurements

This study measured anthropometric data of participants (Table 2). The relationship between anthropometric data, comfort and discomfort was also calculated (Table 3). The data shows that the correlation is higher the shorter the pitch is. In the 28-inch seat pitch, all anthropometric measurements were found to be significantly correlated at p=0.01 with comfort. While only sitting height, eye height seated, and popliteal height with shoes on were found to be correlated with discomfort in the 28 inches setting at p=0.01. Popliteal height sitting with shoes were found to be significant at 0.05 level r=0.-194 with overall discomfort at 32 inches seat pitch. There was no significant correlation between any anthropometric measurements and neither comfort nor discomfort for the 34-inch setting and only one at p=0.05 at the 32 inches setting, namely popliteal height. Results did not show correlations between eye height seated and comfort, as well as buttock to knee and discomfort in the 34-inch seat pitch. It was found that the difference between the effect of anthropometry on comfort and discomfort is not that large, which might perhaps support the statement of Ahmadpour et al. [13] that in aircraft interiors the comfort and discomfort could be on one axis, but further research would be needed to support this statement, though it might also be due to the short time sitting in the seat. While Smulders et al. [25] and Li et al. [9] showed that discomfort does increase over time.

The anthropometric measurements taken in this study were compared to the anthropometric measurements of the Dutch students [21] and it was found that both measurements were similar [12]. Molenbroek et al. [21] found the anthropometric measurements in the last 30 years did not change much, except for hip-width. This shows that these results will be still relevant for design in the future for most anthropometric values.

Table 2. Anthropometric Measurements of Participants

Anthropometric Measurements	n	p5	p95	mean
Sitting height (mm)	88	831	1003	906
Eye height seated (mm)	88	720	899	801
Buttock to knee (mm)	88	472	695	596
Popliteal height sitting with shoes (mm)	151	423	510	466
Stature (mm)	88	1600	1937	1762

Table 3. Spearman's Correlation of Anthropometric Measurements to Overall Comfort and Overall Discomfort.

Measurements	n	28 inches		30 inches		32 inches		34 inches	
		Comfort	Discomfort	Comfort	Discomfort	Comfort	Discomfort	Comfort	Discomfort
Sitting height	88	-.400**	.374**	-.215*	.379**	-.066	.196	.089	-.041
Eye height seated	88	-.329**	.294**	-.266*	.342**	-.045	.068	.035	-.033
Buttock to knee	88	-.343**	.289**	-.271*	.217*	-.089	-.024	-.085	.027
Stature	88	-.510**	.318**	-.317**	.386**	-.153	.189	.026	-.011
Popliteal height sitting with shoes	151	-.460**	.282**	-.313**	.271**	-.116	.190*	-.047	.054

** p-value < 0.01 level (2-tailed)
* p-value < 0.05 level (2-tailed)

Kremser et al. [11] showed a surface plot on the relationship of buttock-to-knee length, seat pitch and well-being. This study tried to replicate this graph of buttock-to-knee length, seat pitch and comfort (10-scale) and found similar results for seat pitch 28-34 inches (see Figure 6). However, the effect of anthropometry seems higher in our study. This could be due to the fact that in our study, a larger range of anthropometric variation is included.

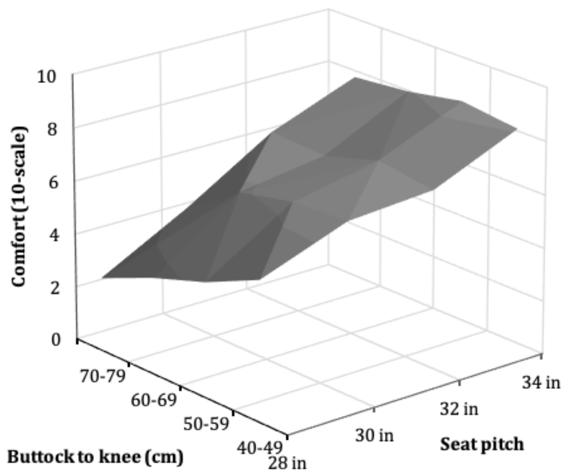


Figure 6. The overall comfort, buttock-to-knee by seat pitch size found in this study.

Space experience and (dis)comfort

All positive descriptors (leading to comfort) were correlated significantly with overall comfort, and negative descriptors (leading to discomfort) were correlated significantly with overall discomfort shown in Table 4. The correlation of space experience descriptors was higher to overall comfort. This might indicate that comfort was influenced more by psychological aspects regardless of whether the descriptors were positive or negative [18]. These space experience questionnaires were filled-in correctly by 167 participants. The questionnaire with missing answers was not included in the calculations.

A Spearman's correlation was performed on pitch size and all space experience statements. Results show all were significantly correlated to pitch size (p<.01). The statement on the backrest was found to be less correlated (r=.162, p=.000) though it was significant. The highest correlation was found in the feeling of being restricted (r=.718, p=.000). These statements derived from the study of Kremser et al. [11] and Menegon et al. [23] were predicted to be correlated with seat pitch size for both comfort and discomfort. The results shown in Figure 7 indicate that these descriptors as psychological factors of comfort and discomfort did effect passengers seating in different pitch size.

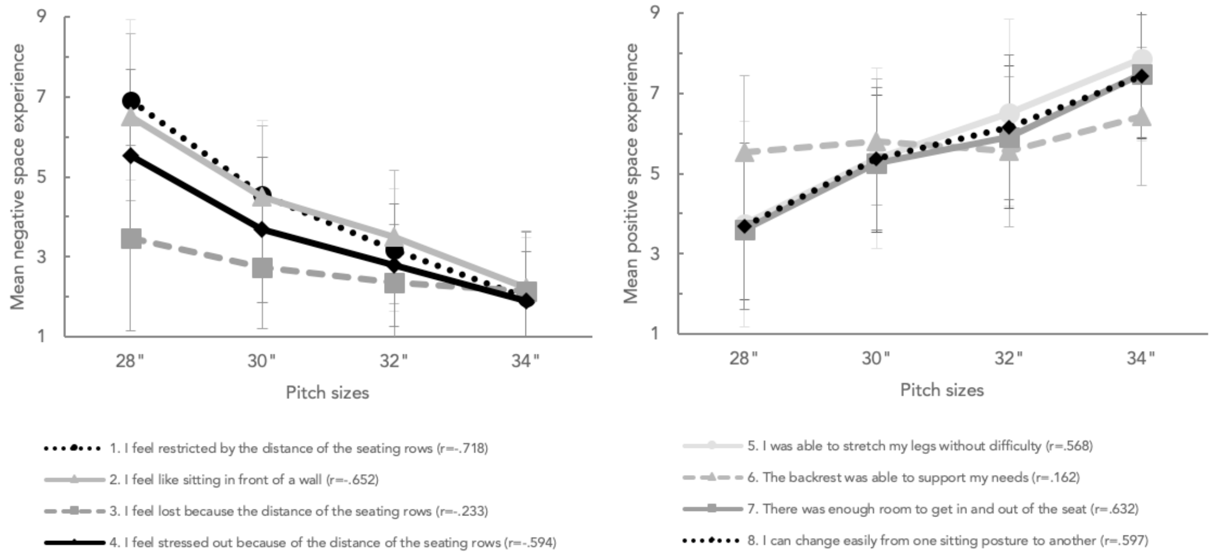
The participants of this study were only asked to sit for a duration of 10 minutes in each seat. As is shown by Smulders et al. [25] studying a business class seat and Sammonds et al. [26] studying a car seat, discomfort increases in time, and this could be the case in economy class seats as well. Future research is needed for long term studies to see the effect of time on (dis)comfort. Body movement/fidgeting and other objective measurements like HRV could be used to evaluate the (dis)comfort, as an addition to having questionnaires for subjective measurements [27]. Seat width as a factor of personal space in an aircraft should be studied in the future as well, especially as hip width is increasing [21]. Moerland [10] describes a relationship between seat pitch and its width on discomfort, which should be studied further. Furthermore, Li et al. [9] found that the effect on seat pitch is larger in time, and Blok et al. [8] found that personal space and seat width is an important factor that ranked after knee space.

Table 4. Spearman's correlation of space experience descriptors, overall comfort and discomfort

Space experience descriptors	Overall Discomfort (CP-50)	Overall Comfort (10-scale)
1. I feel restricted by the distance of the seating rows	.601**	-.747**
2. I feel like sitting in front of a wall	.508**	-.682**
3. I feel lost because the distance of the seating rows	.275**	-.280**
4. I feel stressed out because of the distance of the seating rows	.482**	-.646**
5. I was able to stretch my legs without difficulty	-.515**	.623**
6. The backrest was able to support my needs	-.264**	.386**
7. There was enough room to get in and out of the seat	-.559**	.713**
8. I can change easily from one sitting posture to another	-.577**	.758**

** p-value < 0.01 level (2-tailed)

It is clear that anthropometric data, as well as psychological gathered data, have an influence on the discomfort and comfort of aircraft seats. The study shows that a 28 inches pitch results in very low comfort scores (4 on a scale from 1-10), which is the agreement with the study of Moerland [10] and Kremser et al. [11]. It is not only the physical hip-to-knee distance of the seat which causes this discomfort but also other physical and psychological factors play a role, which might be very relevant to airlines. Anthropometric measurements referring to width were not recorded although it might influence the perception of comfort, especially for the middle seat. Participants were allowed to talk to each other, which potentially influences their decision to rate the seat. Participants involved belonged to a specific age range and nationality, which could not represent the whole group of airplane travellers.



(a) (b)

Figure 7. The relationship of (a) negative and (b) positive space experience to seat pitch.

Conclusion

The aim of this study was to investigate the relationship between seat pitch and (dis)comfort, and what the influencing factors are, like space experience and anthropometric data. This study has found a significant relationship between seat pitch and comfort as well as discomfort. An analysis was also done on the location of the seat, where it was found that the mean discomfort of each pitch size for the seat was higher than the window and aisle seat, though seat pitch had a higher effect on the (dis)comfort in comparison to seat location.

We also found that anthropometric sizes significantly affect the (dis)comfort of smaller pitch sizes. In the 28 inches seat pitch setting, the sitting height, eye height seated, buttock-to-knee, stature and popliteal height sitting with shoes were all found significant at 0.01 level. None of the anthropometric measurements was found significant on the 34 inches seat pitch. This shows that comfort will rapidly decrease for people with larger body dimensions in shorter seat pitch.

All comfort and discomfort statements on space experience had a correlation to the pitch sizes. The statement on feeling restricted had the highest correlation (r=-.718), while the statement on the backrest support had the lowest correlation (r=.162). This shows that space experience as a psychological factor is relevant to the comfort of passengers. The space experience statements were also significantly correlated to both comfort and discomfort. A stronger relationship was found between both negative and positive space experience descriptors to comfort. This might indicate that comfort is more related to psychological aspect regardless of the positive and negative sentences.

Future research is needed for long term studies to see the effect of time on (dis)comfort. Body movement and other objective measurements could be added as well to evaluate the (dis)comfort as an addition to questionnaires.

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The effect of 17-inch-wide and 18-inch-wide airplane passenger seats on comfort

Abstract

The pitch and width of airline seats are crucial factors in the comfort of passengers. The aim of this study is to measure the comfort feeling of passengers regarding different widths and together with data from a previous study, to offer suggestions on the aircraft interior design. 311 participants were recruited and were asked to sit in 17-inch-wide and 18-inch-wide aircraft seats in a Boeing 737 fuselage for 10 minutes, respectively. Questionnaires on psychological comfort and overall discomfort, as well as an additional questionnaire on the discomfort of different body parts, were used to evaluate the comfort and discomfort experience of participants. Experiment results indicated that the comfort scores were significantly higher, and the discomfort scores were significantly lower for sitting on the 18-inch-wide seats than that of sitting in the 17-inch-wide seats. It was also found that rather than the buttock, the shoulders, knees, lower legs and feet contributed significantly to the reduction in overall discomfort by providing more space for movements. Regarding anthropometric measurements, participants with smaller hip-breadth felt more comfort while sitting the 18-inch-wide seat, which highlights the importance of freedom of movement. By synthesizing the results of a previous study on the relations of the seat pitch and comfort, it was found that given the same amount of additional floor area, widening the seat is more effective on comfort than increasing the pitch.

Relevance to industry: This discovery might be useful for the airline industry for more effective and efficient usage of floor area.

Keywords: Comfort, seat, width, airplane

Introduction

The selection of carriers for air travellers are influenced by many factors. Besides the basic needs such as the convenience of the route, the departure time and the price, comfort is one of the most important criteria, especially for business travellers [1, 2].

Passengers experienced different activities during air travel. Among those activities, they spend most of their time sitting during the flight [3]. Offering the comfort seating experience is therefore crucial for airlines for attracting customers. An earlier study of 861 passengers by Richards and Jacobson [4] found that seat width was linearly correlated to the level of satisfaction of passengers based on a comparison of data collected from 4 different airlines. Hinninghofen and Enck [5] further identified that seat comfort was associated with seat pitch, seat width, legroom, quality of upholstery, and possibly, the angle of recline. Vink et al. [6] also found that seat width was important for passenger comfort provided that bigger armrests should not reduce the space for sitting. Besides, the width and pitch of the seat were also primary factors for passengers to upgrade to the premium economy class based on their previous experience [7].

Body dimension is an important aspect to consider in designing for large populations, e.g. having both the small woman (P5) and the large man (P95) fit in the airplane seat [8]. Besides, the changes of anthropometric measurements of populations over the past decades should also be considered, as Molenbroek et al. [9] found a 2% increase per decade in hip-breadth of the Dutch population in 30 years and recommended a new standard for designers regarding the width of the seat. Quingley et al/ [10] also proposed the need to update the minimum seat pitch requirements, as the UK Airworthiness Notice 64 requirements made in 1989 currently only fits P88 British, P77 European and P80 World population. Porta et al. [11] measured 547 participants in Spain and concluded that it is necessary to increase both the minimum seat pitch and the seat width in the economy class. The increments in both/either pitch and width would surely bring more comfort to the passenger. However, due to the limited floor areas, the priority of increasing the pitch or widening the seat remains a question.

In summary, the literature study indicated that widening the seat will improve the comfort of passengers. However, space is valuable in an aircraft. While airlines try to accommodate more passengers of an airplane for profits, offering comfort experience in a given limited floor area is always a challenge. This leads to the research questions of this paper: 1) What is the comfort experience of widening a seat from 17 inches to 18 inches on comfort? and 2) Whether widening the seat or increasing the pitch is more effective in floor planning regarding the comfort feeling of passengers?

Materials & Method

An experiment was designed to study the comfort of passengers regarding the widths of seats. Fourteen 17-inch-wide seats and fourteen 18-inch-wide seats were installed in a Boeing 737 fuselage. The pitches of all seats were kept the same (30 inches). 311 participants were invited to the experiment in 12 sessions, which were held consecutively in 3 days. Prior to the experiment, participants measured their anthropometric data which included shoulder breadth, hip breadth, elbow to elbow breadth, waist breadth, sitting elbow height, sitting shoulder height, and stature of participants following the DINED procedure [9]. The weight of the participants was also measured for calculating their Body Mass Index (BMI). At the beginning of each session, the protocols of the study were explained to the participants and participants were asked to sign the consent form. Participants who did not want to share their data were excluded from the study. Then, half of them started by sitting in the 17-inch-wide seats and the other half with the 18-inch-wide. After 10 minutes, the two groups switch their seats for sitting another 10 minutes. The complete session lasted approximately 30 minutes. In the experiment, the location of each participant was kept the same in both scenarios, e.g. if a participant first sat on a 17-inch-wide window seat at the left, he/she also sat on the 18-inch-wide window seat at the same side.

All seats were adjusted to an upright position. Therefore, the inclination angles of the seats were the same. Participants were instructed to maintain the upright posture, though the actual posture was freely chosen. Every time after 10 minutes sitting in the seat, participants were asked to complete three questionnaires, i.e. a questionnaire on psychological comfort, a CP-50 scale on discomfort [12] and a Local Perceived Discomfort (LPD) body map [3]. The reason for using these three types of questionnaires is that discomfort is more related to physical factors and for comfort, besides physical factors, psychological and social factors should be considered as well [3, 13–16].

Eight statements used in the psychological comfort questionnaire (listed in Table 2) were derived from studies of Kremser et al. [14], Menegon et al. [15] and The Future Lab [17], and the positive and negative descriptors suggested by Helander and Zhang [18] were adopted. A "Not Applicable" option was added as an option for each question to see whether a question(s) fits the condition well. The CP-50 discomfort scale was selected as this two-stage questionnaire is able to give a holistic view of the discomfort of the subject [12], where for evaluating discomfort regarding different regions of the body while sitting, the LPD body map with the Numerical Rating Scale (NRS) introduced by Li et al. [3] was used.

The validity of the answers of the questionnaires was checked first. The number of valid datasets is reported in each analysis where incomplete datasets were excluded. The anthropometric measurements were compared to the database of Dutch populations [9] as the participants were from the same population. These results were then correlated to the comfort and discomfort results of the questionnaires. Additionally, comfort and discomfort scores of regarding two hipwidth groups were compared, as Molenbroek et al. [9] indicated that human with 434 mm hip width or less is suitable for 17.1" seat width.

Groenensteijn [19] indicated that the feelings of comfort and discomfort were not always a normal distribution regarding the population. A Shapiro Wilk test was conducted to validate the data distribution for selecting proper statistical tools. The Wilcoxon Signed-Rank tests were therefore selected to evaluate the differences in the feeling of comfort/discomfort regarding different seat widths as this method is suitable for analysing data that is not normally distributed. A Spearman's correlation was conducted to explore the relations between comfort/discomfort and the dimensions of each body dimensions regarding the seat widths. The significance and correlation of LPD results were calculated individually on each body part. IBM SPSS 25 was used for all statistical calculations. Furthermore, the linear regression method was used to associate the discomfort of each body part to the 10-scale overall comfort and the CP-50 discomfort, respectively. The coefficients of the regression models were then analysed to highlight the importance of discomfort of each body part regarding the overall feeling of comfort/discomfort.

Finally, the results of comfort and discomfort of the two types of seats (17-inch-wide and 18-inch-wide) were synthesized with the results of a previous study [20], which evaluated the feeling of comfort/discomfort of passengers regarding the pitch lengths of the 17-inch-wide seat in the same Boeing 737 fuselage with a similar age group. The comfort and discomfort results of all seat arrangements were normalized and placed into a single graph. The synthesized results of these two experiments cast a new view on the comfort/discomfort regarding the seat pitch and width.

Results

Participant demographic characteristics

Out of 311 participants that participated in the study, 1 person did not wish to share the data for research and the data was excluded in the analysis, resulting in 310 datasets. Among 310 datasets, 193 valid anthropometric measurements were identified where 78 are males and 118 are females. The mean age of the participants is 18.33 years with a standard deviation of 0.74. Details of anthropometric measurements are presented in Table 1 together with the reference database [9]. It can be found that the measurements of participants are very close to that of the reference with a mean absolute error of 3.9%.

Table 1. Anthropometric measurements and comparison to the reference data.

Average anthropometric measurements	This study		Reference [9]		Difference	
	Male (n= 78)	Female (n= 115)	Male	Female	Male	Female
Shoulder breadth (mm)	442	414	457	418	-3.3%	-1.0%
Hip breadth (mm)	364	386	438	382	-16.9%	1.0%
Elbow to elbow breadth (mm)	452	428	438	402	3.2%	6.5%
Waist breadth (mm)	446	412	-	-	-	-
Sitting elbow height (mm)	250	261	260	259	-3.8%	0.8%
Sitting shoulder height (mm)	626	617	-	-	-	-
Stature (mm)	1818	1655	1821	1698	-0.2%	-2.5%
BMI (kg/m2)	21.95	21.33	-	-	-	-

The effect of an increase of seat width on comfort and discomfort

The results of the questionnaire indicate that the scores of participants on comfort is higher when they were sitting in the 18-inch-wide seats (7.72±1.13, n=263) than that when they were sitting in the 17-inch-wide seats (5.90±1.48, n=263). The results of the CP-50 discomfort rating also show that the average overall discomfort for participants sitting in 18-inch-wide seats were in the medium discomfort category (23.09±9.64, n=263), while the 17-inch-wide seats resulted in the low discomfort category (14.44±9.70, n=263).

A Shapiro Wilk test was done to test the normality of the data. It was found that the results were not normally distributed for comfort (p=0.000) and discomfort (p=0.000) at both widths. Furthermore, a Wilcoxon Signed Rank test was used to identify the significances of the effect of widening seat regarding comfort/discomfort. It was found that the comfort scores of using the 18-inch-wide seats are significantly higher than using the 17-inch-wide seats (Z=-12.224, p=0.000, n=263). The results of the discomfort rating also show a significant difference (Z=10.184, p=0.000, n=263)

The psychological effect of the increase of seat width

The results of the questionnaires (n=263) are shown in Table 1. A Wilcoxon Signed Rank test was done and statistical significance was found in all statements (p<0.001) regarding the Z-value respectively (-11.009, -10.072, -11.355, -10.033, -3.608, -8.955, -6.741 and -10.785). The questionnaires included a "Not Applicable" option in the statements. This enables participants to eliminate statements that do not match their psychological condition. It was found that 14.9% of participants thought that the "The seat was wide enough for my body to fit" was "Not Applicable" in determining their psychological comfort, while for other statements, the "Not Applicable" rates were within the range of 0.5%~3.9%.

Table 2. The feeling of comfort of participants sitting in 17-inch-wide and 18-inch-wide seats

Psychological comfort statement	17-inch-wide (9-scale*)	18-inch-wide (9-scale*)
1. I feel restricted by the seat-width	4.35±2.05	2.36±1.54
2. I feel restricted by the distances of the armrests	5.20±2.25	2.99±1.81
3. I feel restricted by my seatmate	5.03±2.25	2.54±1.81
4. I feel stressed out because of the seat-width	3.45±2.08	1.97±1.42
5. The seat was wide enough for my body to fit	7.04±2.32	7.38±2.54
6. I can change easily from one sitting posture to another	4.99±2.32	6.54±2.24
7. The seat-width enhances my productivity	4.07±1.98	5.08±2.15
8. The width of the seat makes me relaxed	4.20±2.00	6.49±2.06

*1: extremely disagree; 9: extremely agree

The physical effect of the increase of seat width

The anthropometric measurements were correlated to the scores of comfort and discomfort using Spearman's correlation method. Table 3 presents the results.

Table 3. Spearman's correlation of anthropometric measurements to comfort and discomfort.

Anthropometric measurements (n=194)	Comfort		Discomfort	
	17-inch-wide	18-inch-wide	17-inch-wide	18-inch-wide
Shoulder breadth	-.070	-.154*	.043	.092
Hip breadth	-.172*	-.092	.052	.183*
Elbow to elbow breadth	-.133	-.121	.167*	.087
Waist breadth	-.098	-.121	.093	.073
Sitting elbow height	-.038	.055	-.019	-.036
Sitting shoulder height	-.231**	-.187**	.044	.045
Stature	-.192**	-.262**	.048	.185*
BMI	-.121	.125	.148*	-.076

**Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Generally, the mean scores of the LPD body map were low for each body part both in using the 17-inch-wide and 18-inch-wide seats (Table 4). Wilcoxon Signed Ranks tests (n=294) were conducted to compare the differences between using two types of seats regarding each body part Test results indicate that there are significant differences between using the 18-inch-wide seats and using the 17-inch-wide seat for all body parts except for the lower back (Z=-.127, p=.899)., where participants felt less uncomfortable sitting in 18-inch-wide seats.

Table 4. Discomfort Scores of the LPD body map

Body part	17-inch-wide (5-scale*)	18-inch-wide (5-scale*)	p-value
1. Head & Neck	2.64±0.96	2.18±0.92	.000
2. Shoulders	2.31±0.97	1.99±1.02	.000
3. Arms	2.55±1.08	1.93±1.03	.000
4. Upper & Middle Back	2.35±1.06	2.19±1.09	.090
5. Lower Back	2.43±1.13	2.42±1.13	.899
6. Buttocks	2.36±1.12	2.07±1.12	.002
7. Thighs	2.11±1.06	1.80±1.06	.000
8. Knees	2.54±1.33	1.99±1.21	.000
9. Lower legs & feet	2.30±1.16	2.04±1.14	.003

*1: not uncomfortable; 5: extremely uncomfortable

To explore the relations of the results between the LPD and the overall comfort/discomfort, a linear regression model was used to fit scores of each item in the LPD to the overall comfort and discomfort, respectively. Here c_i are coefficients of component i of the LPD and c_0 is the intercept of the regression model. Table 5 presents all coefficients regarding the comfort/discomfort of two types of seats. Regarding comfort, for the narrower 17-inch-wide seat, the absolute value of c_2, c_5, c_8, c_9 are larger than the rest, which indicates the importance of discomfort of the shoulder, the lower back, the knee and the lower leg and foot to the overall comfort in this situation. For the 18-inch-wide seat, the discomfort of the arm, the upper and middle back, the lower back and the knee were found be of importance. In both cases, the signs of those large coefficients are negative, which indicates that discomfort in those areas is inversely correlated with people's perception of comfort. For discomfort of sitting in the 17-inch-wide seat, the most important factors on the overall discomfort are the discomfort of the upper and middle back, the lower back, the shoulders and the lower legs and feet and for the 18-inch-wide seat, they are the arms, the lower back, the buttocks and the shoulders. The signs of those large coefficients in both seats are positive, which highlights the positive correlations between local discomfort and overall discomfort.

$$\text{Overall comfort/discomfort}=c_0+\sum_{(i=1)} c_i \, LPD_i$$

Table 5. Coefficient of regression.

No.	Body Part(s) - LPD_i	Comfort		Discomfort	
		17-inch-wide	18-inch-wide	17-inch-wide	18-inch-wide
c_0	-	0.780	0.860	0.149	0.014
c_1	Head and neck	-0.001	0.0001	0.007	-0.002
c_2	Shoulders	-0.014	-0.001	0.023	0.030
c_3	Arms	-0.004	0.010	0.015	0.024
c_4	Upper and middle back	-0.006	-0.016	0.017	0.001
c_5	Lower Back	-0.020	-0.014	0.019	0.025
c_6	Buttocks	0.005	-0.007	0.007	0.026
c_7	Thighs	0.011	0.003	-0.006	0.007
c_8	Knees	-0.016	-0.010	0.015	0.022
c_9	Lower legs and feet	-0.036	-0.008	0.032	0.004

The coefficients of comfort regarding sitting in two types of seats were found to be strongly correlated (r=0.99), which indicates the consistency of the relations between the scores of the LPD body map and comfort in two scenarios. Regarding the overall discomfort, we did not find correlations between coefficients of the regression model in two scenarios. The comfort and discomfort scores were further categorized into 2 groups based on the 17-inch-wide seat width where 432 mm was used as the threshold based on the width of the seat and data from the literature [9]. The mean values and the standard deviation were calculated for both groups regarding comfort and discomfort (Table 6) and compared. The stature and sitting shoulder height was found to be significantly correlated with comfort, most probably due to the fact that the average height of Dutch is tall (1818 mm for male and 1655 mm female). The group with a larger hip breadth benefited more by the widening of the seats (Table 6). Even though the seat is still smaller than their hip breadth, adding an inch did make a difference for this group.

Table 6. Means and standard deviation of hip breadth groups.

Hip Breadth Category	Comfort (1-10 scale)		Discomfort (0-50 scale)	
	17-inch-wide	18-inch-wide	17-inch-wide	18-inch-wide
> 432 mm = 17” (n=178)	6.0±1.5	7.6±1.1	22.3±10.0	14.9±9.8
≤ 432 mm = 17” (n=15)	5.6±1.5	7.8±0.9	25.8±7.0	13.2±8.8
> 457 mm = 18” (n=196)	6.0±1.5	7.6±1.1	22.3±9.9	14.9±9.8
≤ 457 mm = 18” (n=10)	4.9±1.4	7.8±1.0	27.5±6.8	11.8±7.4

Comparison of increasing width and pitch

In a previous study [20], the comfort and discomfort of participants regarding sitting in a 17-inch-wide seat with different pitches were studied in a similar setup with a similar population. Comparing the results of this experiment to the results of the previous study (Figure 1 and Figure 2), it was found that the comfort scores of the 17-inch-wide wide and 30-inch-pitch were similar (6.00±0.09 vs 6.03±0.12). The one-inch increment of seat width resulted in an increase in comfort score of 2.0 (on a scale of 1-10) and a decrease in the discomfort of 8.7 (on a scale of 0-50). This result is a lot higher compared to increasing the seat pitch by two inches, which increased the comfort 0.7 and decreased the discomfort 4.0.

The overall comfort and discomfort were normalized to 1 and plotted in Figure 3 to show the relationship between comfort and discomfort regarding the pitch and the width of seats. The figure shows that there is an overlap between comfort and discomfort of all scenarios, i.e. the sum of normalized mean values of comfort and discomfort is always larger than 1.

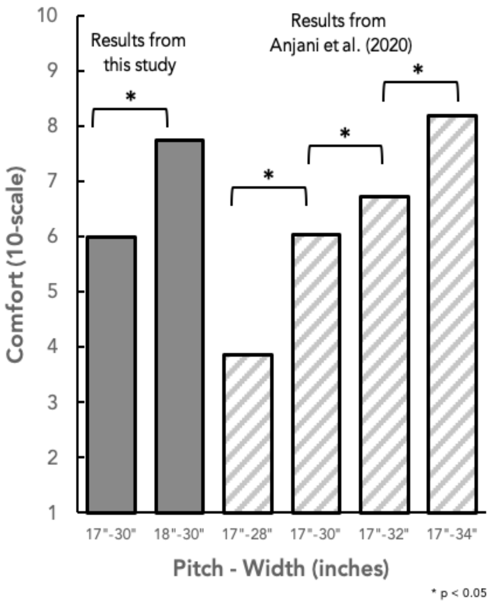

Figure 1. Comfort vs seat width and pitch

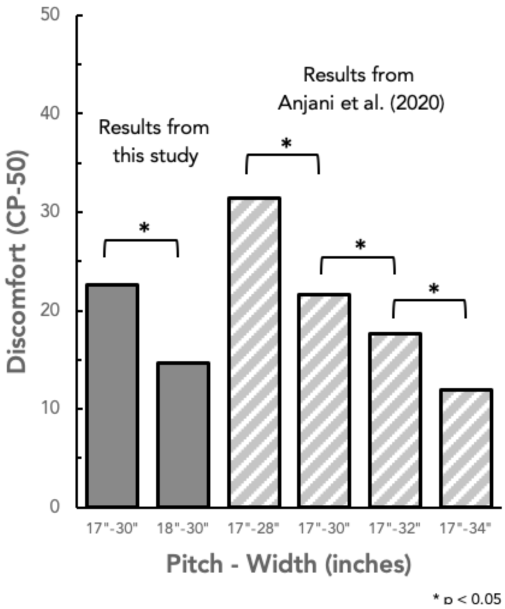

Figure 2. Discomfort vs seat width and pitch

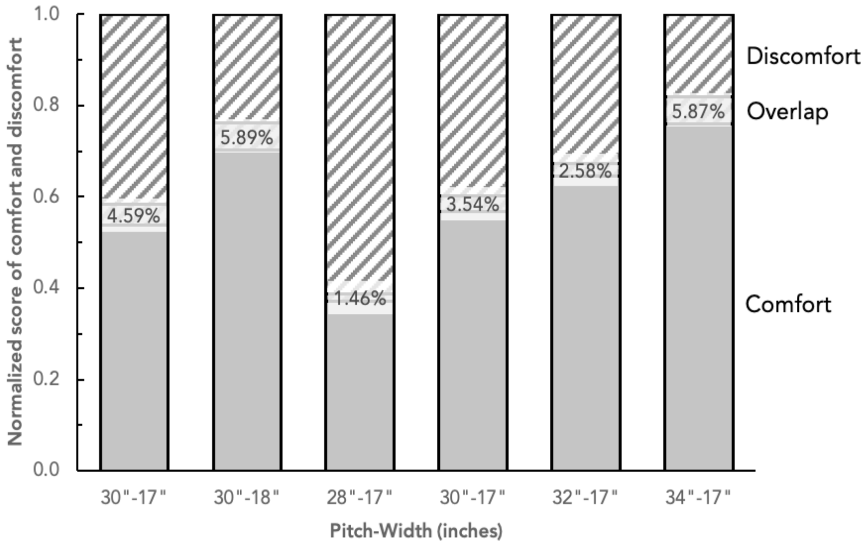

Figure 3. Normalized averaged comfort and discomfort scores vs seat width and pitch

Discussion

Three hundred eleven participants joined this study, which focused on comparing (dis)comfort of participants sitting in seats with different widths for 10 minutes. Questionnaires were given to explore the influence of seat widths on the overall psychological and physical feeling of comfort/discomfort as well as discomfort regarding different parts of the body. In addition, the results were synthesized with the outcomes of a previous study where 297 participants experienced sitting it 17-inch-wide seats with different pitches for 10 minutes [20].

This study collected data of psychological perception of comfort using 8 statements with a 9-scale Likert (similar to Kremser et al. [14]). Responses to all statements differed significantly between using the 17-inch-wide and the 18-inch-wide seats. It was also found that one statement had a higher “Not Applicable” rate than other statements, which was “The seat was wide enough for my body to fit”. The reason might be that the interpretation of the “fit” is not only based on physical measures, but also on psychological factors, e.g. people need more space to move around and change postures.

A Shapiro Wilk test was done to test the normality of the comfort and discomfort data. It was found that the data for this study was not normally distributed, therefore all data were analysed using a non-parametric statistical analysis. This result was in-line with literature indicating that comfort and discomfort data is not normally distributed [19].

These anthropometric measurements taken are highly comparable to the data of Molenbroek et al. [9] (e.g. Female/Male elbow-to-elbow breadth average = 429/455 mm vs 402/438 mm). It was found that for the 17-inch-wide seat, the wide hip groups had a lower comfort score and such situation did improve by adding 1-inch to the width. This indicates that the body should not exactly fit in the chair. A space to allow movement is needed.

For people with a wider elbow-to-elbow breadth and shoulder breadth, the width of a seat is important regarding comfort [8, 9]. This study did not find the correlation between comfort and discomfort scores of the participants to those anthropometric measurements. This might be that for a short-term study, the psychological factors are more important. However, such an impression could be changed after experiencing physical factors in the long run [21].

Regarding the LPD, it was found that all body parts except for the buttocks were significantly influenced by the seat width. This indicates that buttock discomfort is not related to seat width, but perhaps more to the quality of the seat cushion. Furthermore, a linear regression on comfort and LPD was made and showed that in the area of shoulders, knees, and lower legs and feet, there were increments in comfort from sitting in 17-inch-wide to 18-inch-wide seats. Same as the discovery before, a wide seat may facilitate the feeling of comfort and decrease the feeling of discomfort by providing more spaces for movement.

According to Li et al. [3] "The overall discomfort was the average of the all parts' discomfort ratings… based on an assumption that all body parts' discomfort have the same weight for the overall discomfort." In our case, we asked about discomfort per body part and additionally the total discomfort. It was interesting to see that the head and neck, shoulders, buttock, and thighs were affected by the seat width on the total discomfort, and the total discomfort was not related to the average of the LPD results. This indicates that discomfort has different relations regarding different parts of the body.

In answering the research questions, it was found that there is an increased feeling of comfort and decreased feeling of discomfort by widening the seats from 17 inches to 18 inches. Moreover, the level of comfort of sitting in an 18-inch-wide seat was nearly the same as sitting in a 17-inch-wide seat with 4 inches extra pitch. Therefore, to achieve the same level of comfort, it is more efficient for airlines to increase the width than the pitch regarding a 17-inch-wide seat, as the additional floor area (0.02m^2) of widening 1 inch of the seat is the same as increasing the seat pitch for 2 inches (0.02m^2) as shown in Figure 4. To achieve the same increased level of comfort, 4-inch additional pitch is needed, which will cost 200% (0.04m^2 as Figure 5) extra floor area. Figure 6 presents a hypothetical relationship between pitch, width and comfort [22] based on literature. Results from this paper and the previous study were plotted on the graph as well. The experiment results of this paper, in which 30-inch seat pitch with 17-inch-wide and 18-inch-wide width were used, partly affirmed this hypothetical relationship. On the other hand, the results from the previous study did not fit well the hypothetical relationship. This might indicate that the relationship between pitch and comfort is not linear.

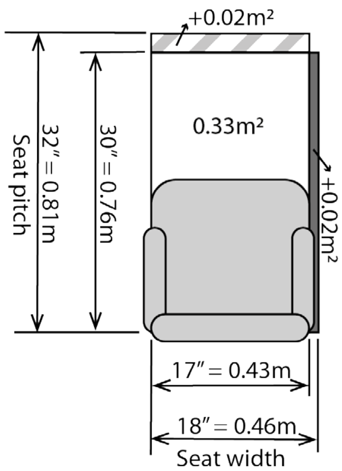

Figure 4. Increasing the pitch and width for the same floor area.

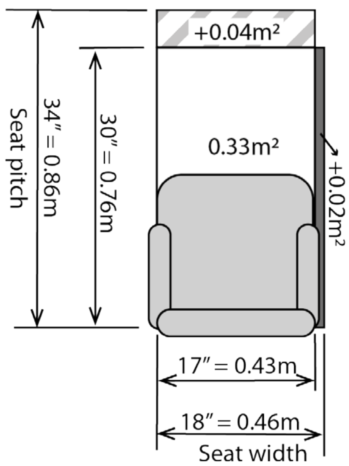

Figure 5. Increasing the pitch and width for the same level of comfort.

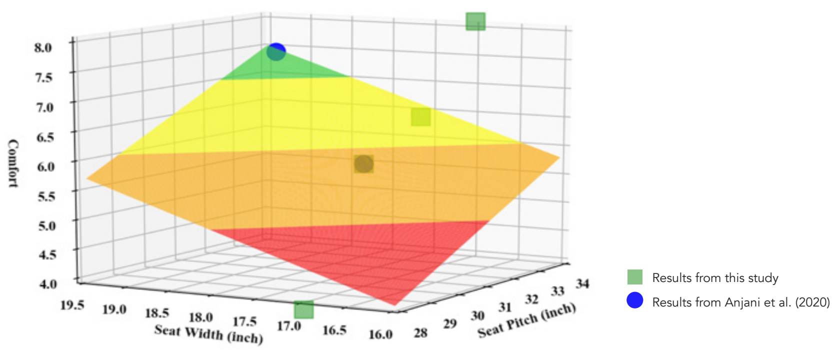

Figure 6. Experiment results and the hypothetical relationship of seat pitch and width graph proposed by Vink [22]

Ahmadpour et al. [23] indicated that "discomfort and comfort could be used on one scale". In this research, we normalized the scores of comfort and discomfort and projected the mean values to the span of 0 and 1. It was identified that there are consistent overlaps between mean scores of comfort and discomfort of each pitch (or width) variation (Figure 3), i.e. comfort is not as simple as 1 - discomfort. This might be explained by that comfort and discomfort scales are two different factors rather than one single entity and there is a transition phase between comfort and discomfort as Figure 7 (courtesy of Zhang et al. [16]. Vink and Hallbeck [24] also stated that comfort is "a pleasant state or relaxed feeling of a human being in reaction to its environment" and discomfort as "an unpleasant state of the human body in reaction to its physical environment", which indicate that the feeling comfort might not only based on human body reaction but consist more psychological and social factors.

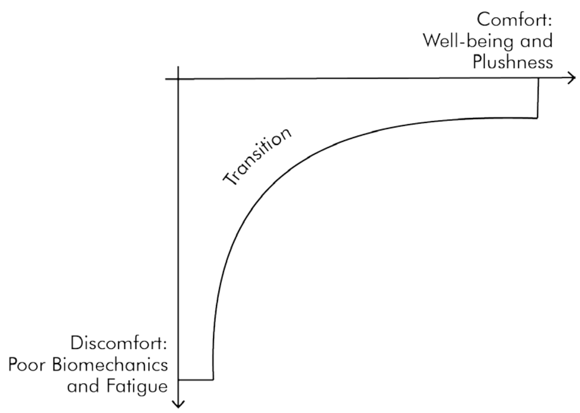

Figure 7. Comfort model of Zhang et al. [16]

One of the limitations of this study is that the experiment was conducted in a relatively short period (10 minutes sitting in each type of seats), which is not comparable with regular flights. Smulders et al. [25] indicated that even after 90 minutes that comfort continuously decreases while discomfort increases. Similarly, Li et al. [3] discovered a constant increase of discomfort over 3 hours. So, it might be that the difference between the two widths would have been larger in a long test. Further studies are needed to test this hypothesis. Besides, in a long-haul flight, sleeping is an activity that most passenger will experience. Airbus indicated that a wider seat is preferred for better sleeping [26] however, only 6 participants participated in the experiment. It is hard to compare that with this study as 10 minutes comfort experience is different from 6 hours sleeping. On the other side, visual aspects that play a role in short term judgments could not be eliminated in this study since the difference in width is clearly noticeable. Such visual experience might be beneficial for short-haul flights regarding the feeling of comfort for passengers.

The participants in this study were young (17-21 years old) which does not represent average air travellers, on the other hand, these are the travellers of the future and according to Mohn [27], they will travel more. Therefore, the collected data is also relevant for designing future aircraft interiors for making efficient use of the space while creating the comfort-experience at the same time.

Conclusion

This study aimed to compare the comfort and discomfort feelings regarding sitting in 2 different seat widths in a Boeing 737 fuselage, and to investigate the psychological and physiological factors that influence those feelings. The results of psychological statements indicated that participants felt more comfort and less discomfort when sitting in the 18-inch-wide seats than that of sitting in the 17-inch-wide seats. Regarding the discomfort of different parts of the body, the results of LPD also indicated significantly reduced discomfort while using an 18-inch-wide seat except for the buttocks. Further analysis using linear regression models revealed that the lower discomfort scores of shoulders, knees, and lower legs and feet contributed to the reduced discomfort, which highlighted the importance of passengers' freedom of movement facilitated by the extra width provided by the 18-inch-wide seat.

By synthesizing the data of a previous study on various pitch sizes, it was found that to reach a similar level of comfort, increasing the width of a 17-inch-wide seat might be more efficient than increasing the pitch regarding the usage of floor areas. This discovery might be useful for airlines in designing a more effective and efficient floor planning of future aircraft.

Acknowledgement

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CHAPTER 3

Human Body Effects

This chapter is based on:

Anjani S, Song Y, and Vink P (2020) HRV, seat, comfort and discomfort relationships over time. Manuscript submitted for publication.

HRV, seat, comfort and discomfort relationships over time

Abstract

This research aims at exploring the relations between heart rate variability (HRV) parameters and subjective feelings of comfort/discomfort of passengers sitting in different economy class aircraft seats over time. A 2-hour study was designed with 16 participants on two different seat pitches (28 inches and 30 inches) and two different seat widths (17 inches and 18 inches) with different tasks. Comfort and discomfort were recorded every 15 minutes by questionnaires and heart rate was monitored constantly. Subjective assessments show that the 18-inch-wide and 30-inch-pitch seat with the largest seat space performed the best in comfort and had the lowest discomfort. The seat with the least space did not perform the worst, which might be caused by the tray table. Subjective assessments showed that discomfort increased over time, while comfort remained constant. In-line with the subjective assessment, HRV parameters did not change much with the increased space. Overall, it was found that some HRV parameters can indicate the comfort and discomfort experience of the participants over time. Comfort was found to be related to more HRV parameters that are correlated to well-being, emotions and psychological states. The HRV parameter SDNN, HF and SD2 seem promising as it has the strongest relationship with comfort and is fairly easy to record where the changes over time could be detected.

Introduction

In selling tickets for a train or airplane and in selling cars, seat comfort is an important factor [1]. Many researchers make a distinction between comfort and discomfort. Helander and Zhang [2] found that discomfort is more related to poor biomechanics and fatigue while comfort is more connected to well-being and luxury; and the reduction of discomfort does not necessarily increase comfort. According to the difference in attributes of comfort and discomfort, many subjective and objective measures were proposed by researchers in the past decades. For instance, more than 15 types of subjective questionnaires were developed [3]. Objective data on comfort and discomfort are hard to gather during use [4]. Pressure distributions have shown to have a relationship with discomfort [4]. However, slippery large mats between the human and the seats could influence discomfort experiences. Skin conductance [5], electroencephalography (EEG) [6], etc. were also introduced to assess comfort/discomfort as objective measures. Among those objective measures, using heart rate variability (HRV) parameters might be promising due to the wide availability of the equipment and the easiness in the deployment [7, 8]. As heart rate is linked to emotion [9] it might have a relationship with comfort. Le and Marras [8] found that the recording of HRV was different for each workstation, and HRV as an indicator of discomfort increased over time, while Weston et al. [10] could differentiate the interactions between chairs and devices with HRV recordings. Therefore, we studied the relationship of comfort and discomfort with HRV for airplane passengers.

HRV consists of changes in the time intervals between consecutive heartbeats called inter-beat intervals [11]. It reflects the output of the central autonomic network (CAN) and, by proxy, an individual's capacity to generate regulated physiological responses in the context of emotion, e.g. pain, stress [12]. As those responses are important constructs of comfort and discomfort [13], some interpretations of heart rate data, like HRV measures can be used as comfort/discomfort predictors.

In general, parameters of HRV can be categorized into time-domain, frequency-domain and non-linear parameters (see Table 2). Among the time-domain parameters, RMSSD has been used to measure a discomfort reaction and was comparable for uneven durations [14]. pNN50 is another HRV parameter used in detecting stress [15]. RMSSD, SDSD, Mean RR and pNN25 were also found as predictors of thermal comfort [16]. In the frequency-domain, the most frequently used parameter is the LF/HF ratio, where it could detect the psychological state of an individual [17], stress level [18], thermal comfort [7, 19] and emotion and empathy in post-stress communication [20]. For instance, Le and Marras [8] explored the relations between the discomfort of using different workstations and the LF/HF ratio of HRV, and they found that the discomfort measured by the LF/HF ratio is in line with the subjective discomfort of the participant. For non-linear parameters, the width (SD1) and the length (SD2) of the ellipse are two typical parameters of the 2D Poincaré Plot and they were found to be associated with short-term HRV and long-term HRV [21, 22], respectively. Researchers indicated that SD1 and SD2 can be used to predict stress [23, 24] and postures taken during exercise [25]. Das et al. [26] introduced the 3D Poincaré Plot and identified that changes in SD1, SD2 and SD3 are associated with the reduction of stress after listening to music. Moreover, other non-linear parameters such as the cardiac sympathetic index (CSI) was found to be significantly higher in stressed conditions compared to non-stressed conditions [27]. SD1, SD2, CSI and cardiac vagal index (CVI) were found to be sensitive to thermal changes [28]. SD1, SD2 and CVI also differ during exercise, rest and recovery period for older men doing prolonged work in the heat [29]. Different types of parameters can be used together in comfort studies, e.g. Gadea et al. [30] explored all parameters of the HRV in detecting seating discomfort and it was found that LF, HF, SDNN, RMSSD and SD2SD1 were correlated with discomfort though none of these correlations was significant.

Though parameters based on HRV were studied regarding discomfort in many contexts, the relationships of different HRV parameters and comfort/discomfort over time were not fully explored in the context of the aircraft seating. This is relevant as more and more sensors are added in vehicles [4] and discomfort could be monitored in research or real flights and measures could be taken to reduce discomfort or improve comfort. This study aims at exploring the relationship between HRV parameters and subjective feelings of comfort/discomfort of passengers seating in different aircraft seats over time with the following research questions: 1) Does comfort and discomfort change over time regarding different types of seats? 2) Are there any relations between various metrics of HRV and the feeling of comfort/discomfort of passengers and 3) If so, which parameters of HRV can be used in predicting comfort/discomfort over time?

Materials & Methods

To answer the research questions sixteen participants (4 females and 12 males) were studied sitting for 120 minutes in an economy class seat in a Boeing 737 fuselage at the Delft University of Technology. As the study was conducted during winter, heaters and air purifiers were provided to maintain similar conditions as in the airplane, e.g. participants were able to sit comfortably without a warm jacket. Thermal comfort was not observed in this study even though many studies associate parameters of HRV to thermal conditions. The temperature was kept at the same level at 18.4°C ± 3.5°C during the 120 minutes.

A 2×2 repeated measures design was used with two different seat pitches (28 inches and 30 inches) and two different seat widths (17 inches and 18 inches). These four seating conditions (17-28, 17-30, 18-30, and 18-32 in the following text) were spread over four days, but recordings took place at the same time of the day as literature shows that comfort varies over the day (e.g. Bazley et al. [31]). For the arrangement of treatments (orders of different seat sizes), the Latin Square design was applied. The study protocol was approved by the Human Research Ethics Committee of Delft University of Technology on March 9th 2018.

Before the start of each session of the experiment, a consent form had to be completed by the participants. The anthropometric measurements such as stature, shoulder breadth, shoulder–elbow length, elbow to elbow breadth, waist breadth, hip breadth, buttock to knee, popliteal height with shoes, sitting elbow height, sitting shoulder height, sitting height, and eye height sitting were measured using an anthropometer on a wooden seat. Participants were measured with normal indoor clothes and shoes on a measuring chair like the one used by the Institute for Consumer Ergonomics (ICE) [32]. Additionally, the weight of each participant was also recorded. Table 1 shows the anthropometric measurements of the participants. In general, the participants were of average size based on the Dutch population [33].

Table 1. The average and standard deviation of participants' anthropometric measurements

Anthropometric measurements	Female	Male
Stature (mm)	1648 ± 48	1793 ± 43
Weight (kg)	55 ± 5	76 ± 11
BMI	20 ± 2	24 ± 4
Shoulder breadth (mm)	393 ± 9	453 ± 13
Shoulder–elbow length (mm)	393 ± 56	437 ± 81
Elbow to elbow breadth (mm)	348 ± 103	406 ± 115
Waist breadth (mm)	281 ± 53	327 ± 40
Hip breadth (mm)	337 ± 18	362 ± 25
Buttock to knee (mm)	526 ± 17	575 ± 24
Popliteal Height with Shoes (mm)	426 ± 19	466 ± 39
Sitting elbow height (mm)	226 ± 34	251 ± 40
Sitting shoulder height (mm)	585 ± 23	636 ± 23
Sitting height (mm)	855 ± 38	914 ± 21
Eye height sitting (mm)	713 ± 45	789 ± 17

After the measurement, the researcher explained the protocols and participants wore a smartwatch in which a heart rate monitor was embedded. Then participants were instructed to sit on the specific aircraft seat following the designed order of the experiment. During the experiment, the participants were always seated in a window seat and the neighbouring seat was kept empty. The seat belt was fastened and the backrest was kept upright throughout the experiment. Figure 1 presents the setup of a typical scenario of the experiment.

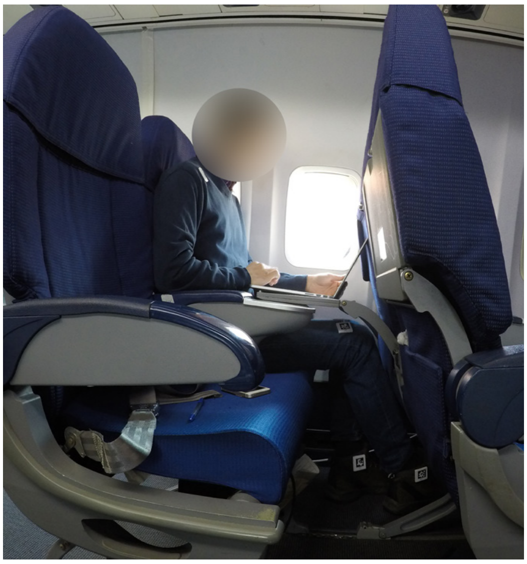

Figure 1. A participant during the experiment

All participants participated in 4 sessions with different seat settings. Each session lasted for about 2 hours. During the session, participants were asked to perform a series of tasks at certain time slots to simulate the activities of a flight (Figure 2). Those tasks include 1) taxi-take off-landing (TTOL), 2) working with a desk (tray table), 3) eating a snack/drinking, 4) working without a desk and 5) a TTOL task again for simulating landing. The duration of these five tasks is 10, 40, 20, 40, 10 minutes, respectively. For the task of working with a desk, participants could use their own laptop on the tray table. During the eating snack/drinking task, participants were allowed to use the tray table. The drink provided was a non-caffeinated drink. For working without a desk, participants were able to read a book.

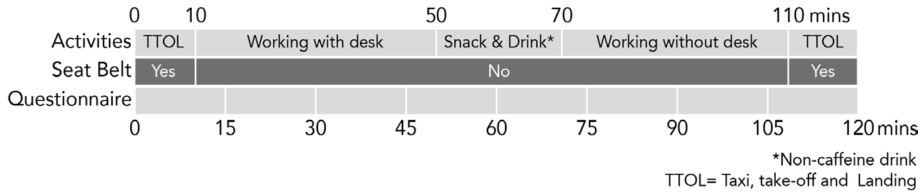

Figure 2. Timeline of the experiment

Before the first TTOL task, participants were asked to complete a questionnaire after being seated. Upon finishing the first questionnaire, the timer was started. Participants were then asked to fill in the same questionnaire every 15 minutes. During the experiment, the sitting posture was not constrained except for the fastened seat belt, i.e. participants can sit naturally throughout the whole experiment process with the seat belt on. It is worth mentioning that participants were not allowed to stand up in the 2-hour session.

A CP-50 discomfort questionnaire and a simple 10-scale overall comfort questionnaire were selected to measure subjective comfort and discomfort, respectively. CP-50 was selected due to the reliability and validity of the scale for measuring discomfort [34]. A simple 10-scale overall comfort score was one of the questionnaires recommended to be used for evaluating the total environment of an end product [3, 35, 36].

The heart rate of the participants was measured using a Mio® heart rate monitor wrist band or an Apple® watch, and the data were collected via a smartphone. The original experiment design used only Mio® heart rate monitor wrist bands which were used in other research [37–39], but during the experiment, some devices did not function correctly anymore. Therefore, an available Apple® watch was used as a substitution for the rest of the experiment. A self-developed Python program was used to extract different types of HRV parameters from the collected data based on the HRV-analysis library [40]. The extracted parameters include time-domain, frequency domain and non-linear parameters as specified in Table 1.

In the analysis of the results of the questionnaires, empty answers were excluded. For frequency-domain parameters of HRV, the Short-time Fourier transform (STFT) method was used with a 5-minute window [60]. Even for long-term HRV parameters such as SD2, the 5 minutes window is still recommended [22]. Due to connection problems, some heart rate data were not recorded by the device. Completely empty heart rate reports of the session were excluded from the analysis, while missing points in the middle of the experiment were filled in with the heart rate data in the previous time frame. The extracted HRV parameters and the scores of the questionnaires were imported to IBM SPSS version 25 for statistical analysis where Pearson's correlation used to identify relationships among different HRV parameters and scores of the questionnaires.

Results

Subjective assessment

The experienced comfort of participants was recorded using a questionnaire. Results showed that the 18-30 seat had the highest comfort scores compared with the other seats, while the seat with the lowest comfort was the 17-30 seat (Figure 3). Using the CP-50 scale for discomfort, the lowest discomfort was found for the 18-30 seat. The seat with the highest discomfort was the 17-28 seat. The scores of the comfort and discomfort questionnaires of all types of seats regarding time (every 15 minutes) are presented in Figure 4. The results also show that for all seat configurations there was an increase of discomfort over time, while comfort remained at a similar level or slightly decreased throughout the experiment.

Zooming in into comfort and discomfort over time for each type of seat setting, it was found that there were a few changes in comfort scores over time (Figure 5). Regarding discomfort, during the 2-hour session, an incremental change over time is identified with significantly correlations (Figure 6, $r=.707$, $p<.001$). It is worth mentioning that the time of the notch of the scores of discomfort (at 75 minutes) was the rime that food and drinks were served.

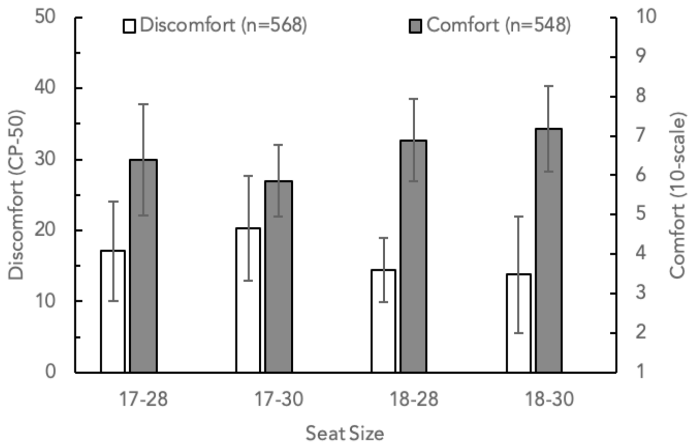

Figure 3. Comfort and discomfort of different seat sizes

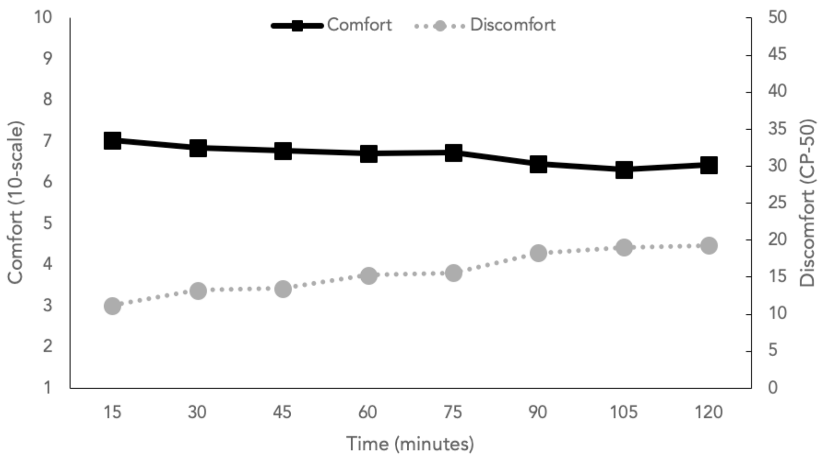

Figure 4. Overall comfort and discomfort for all seat types over time

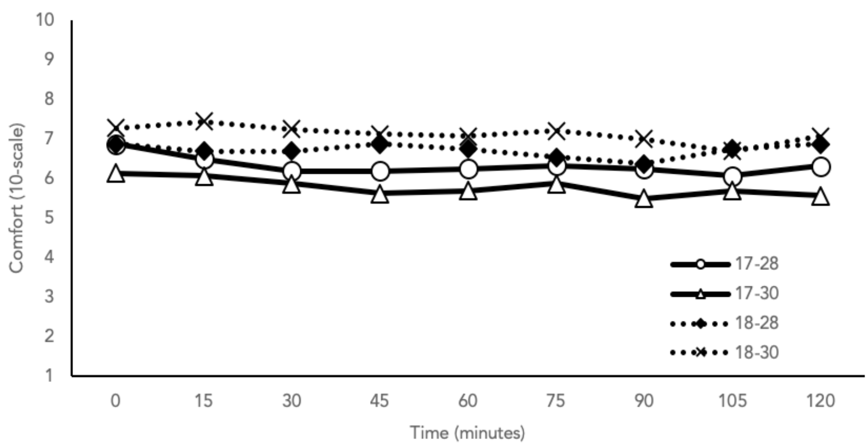

Figure 5. Overall comfort over time

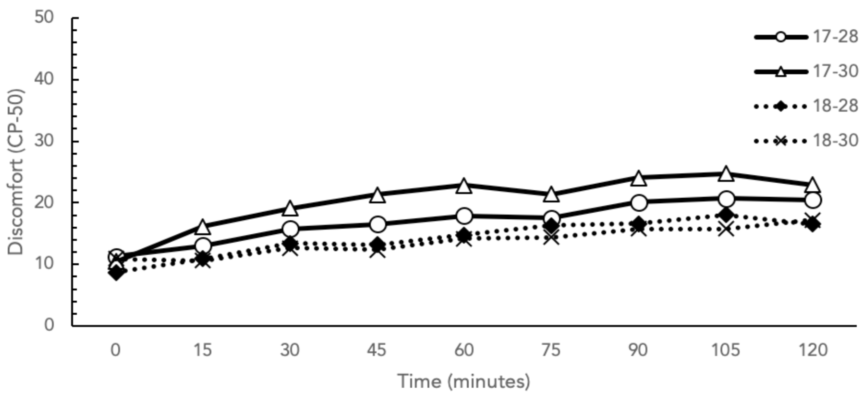

Figure 6. Overall discomfort over time

Table 2. HRV parameters and related physiological or psychological phenomena as described in the literature

HRV parameter	Abbreviation	Metric	Relationships	Measures – human responses (e.g. stress) based on literature	Statistics
Time domain parameters	SDNN	Standard deviation of the time interval between successive normal heart beats (NN intervals) (ms)	Psychological or mental stress	Able to differentiate between the stressful and the non-stressful conditions [27]	Paired t-test (non-stress= 0.65 ± 0.09; stress=0.57 ± 0.07; $p<0.01$)
				Physiological signal: the most discriminating HRV metrics to differentiate the stressful and non-stressful conditions; Psychological stress using State-Trait Anxiety Inventory (STAI) [41]	Physiological signal: One-way ANOVA ($p < 0.0001$) and Tukey multiple comparison test ($p < 0.05$); Psychological stress: Wilcoxon Signed Rank (not significant)
			Physical fatigue or pain	Significantly decreased after high intensive-interval training for trained swimmers [42]	Paired t-test ($p<0.05$)
				Patterns show the presence of fatigue while driving, i.e. awake and sleepy state [413	-
				Correlated to subjective fatigue while driving [44]	Correlation (r=0.26, p<.001)
			Not related	Able to differentiate supine and standing these two postures, but not sitting [45]	One-way ANOVA (not significant)
				Not affected by pain [46]	Two-Way RMANOVA (not significant)
	SDSD	Standard deviation of differences between adjacent NN intervals (ms)	Psychological or mental stress	The best HRV parameter to show a significant change between Trier Social Stress Test (TSST) measured by the mood questionnaire (MDBF) and progressive muscle relaxation (PMR) [47]	One-way ANOVA ($\eta2 = 0.60$, p=.000)
				Decreased for increased stress and able to consistently differentiate the high the low stress levels [48]	Absolute reliability: Mean difference Relative reliability: Kendall's tau Between conditions: paired t-test or Wilcoxon rank sum test
			Physical fatigue or pain	Significantly decreased after high intensive-interval training for trained swimmers [42]	Paired t-test ($p<0.05$)
	pNN50	Proportion of number of interval differences of successive RR-intervals greater than 50 ms (%)	Psychological or mental stress	Changed significantly during stress [49]	Meta-analysis
				Sensitive to changes in mental or physical state even with a minimal physical load [50]	Wilcoxon signed rank test
				Significantly reduced during the time of examinations compared to the holiday periods [51]	Wilcoxon signed rank test (During examinations = 19.038, During holidays= 23.789, p=0.028)
				Able to differentiate between the stressful and the non-stressful conditions [27]	Paired t-test (non-stress= 16.53 ± 14.42; stress=5.93 ±7.04; $p<0.01$)
				Negatively correlated to stress measured using the Perceived Stress Questionnaire (PSQ) and depression measured using the revised Beck Depression Inventory (BDI-II), and positively correlated with well- being measured using The General Well-Being Schedule (GWBS) and good mood measured using Trimmel's Index of Trait Moods (TRIM-T): Good Mood [52]	Correlations (PSQ r=-.36 ($p<0.05$); BDI-II r=-.32. ($p<0.05$); GWBS r=.32 ($p<0.01$); TRIM-T: Good Mood r=.30 ($p<0.05$)
				Differences between the rest and mental stress these two conditions in the Mensa test [53]	Paired and unpaired t-tests or Mann-Whitney U-tests and Wilcoxon signed-rank test ($p<0.05$)

Table 2. HRV parameters and related physiological or psychological phenomena as described in the literature (cont'd)

HRV parameter	Abbreviation	Metric	Relationships	Measures – human responses (e.g. stress) based on literature	Statistics
Time domain parameters (cont'd)	pNN50 (cont'd)	Proportion of number of interval differences of successive RR-intervals greater than 50 ms (%) (cont'd)	Physical fatigue or pain	Significantly decreased after high intensive-interval training for trained swimmers [42]	Paired t-test (p<0.05)
				ecreased while observing physical fatigue at the workplace [54]	Two-factor ANOVA (–34.2%, p<0.05)
			Not related	Not affected by fatigue [55]	One-way ANOVA
				Able to differentiate supine and standing these two postures, but not sitting [45]	One-way ANOVA (not significant)
	pNN20	Proportion of number of interval differences of successive RR-intervals greater than 20 ms (%)	Psychological or mental stress	Physiological signal: most discriminating HRV metrics to differentiate between stress and non-stress these two conditions; Psychological stress: shows positive/negative correlation with psychological stress test using STAI [41]	Physiological signal: One-way ANOVA (p < 0.0001) and Tukey multiple comparison test (p < 0.05); Psychological stress: Wilcoxon Signed Rank (not significant)
				Low pNNxx parameters (pNN10 - pNN40) correlated negatively with stress (PSQ) and depression (BDI-II) and positively with well-being (GWBS) [52]	Correlations (PSQ r=-.40 (p<0.01); BDI-II r=-.36 (not significant); GWBS r=.27 (p<0.01))
			Physical fatigue or pain	Associated with the intensity of experimental electrical pain, but not related to thermal pain. pNN20 was responsive from No Pain to pain, but it tended to recover despite the ongoing pain stimulus [56]	Pearson correlation (Electrical pain for 10 seconds (s) r= -0.1894; 20s r=-0.2437; 30s. r=-0.2894; 40s r=-0.3313; 50s r=-0.3117; 60s r=-0.3471 (p<0.01))
	RMSSD	Root mean square of successive NN interval differences (ms)	Psychological or mental stress	Decreased for increased stress and able to consistently differentiate the high and the low stress levels [48]	Absolute reliability: Mean difference Relative reliability: Kendall's tau Between conditions: Paired t-test or Wilcoxon rank sum test
				Changed significantly during stress [49]	Meta-analysis
				Able to differentiate between the stressful and the non-stressful conditions [27]	Paired t-test (non-stress= 38.53 ± 15.62; stress=24.78 ±8.2; p<0.01)
			Physical fatigue or pain	Detect unpleasant scenarios during driving [14]	Pointwise confidence interval; before unpleasant scenario r=-.21, p <.001; after unpleasant scenario r=.30, p<.001
				Patterns shows the presence of fatigue while driving, i.e. awake and sleepy state [43]	-
				Significantly decreased after high intensive-interval training for trained swimmers [42]	Paired t-test (p<0.05)
			Not related	Able to differentiate posture supine and standing, but not sitting [45]	One-way ANOVA (not significant)
				Not affected by fatigue [55]	One-way ANOVA
	Mean NN	Mean normal-to-normal (NN) interval (ms)	Psychological or mental stress	Mental stress: Significantly affected by mental stress with Paced Auditory Serial Addition Task (PASAT) as the stimulus, and attention to non-painful stimuli. [46]	Two-Way RMANOVA Rest =1031±134 vs. PASAT =805±125, (p<0.001); Rest = 1009±125 vs. Attention = 980±115 (p<0.05)

Table 2. HRV parameters and related physiological or psychological phenomena as described in the literature (cont'd)

HRV parameter	Abbreviation	Metric	Relationships	Measures – human responses (e.g. stress) based on literature	Statistics
Time domain parameters (cont'd)	Mean NN (cont'd)	Mean normal-to-normal (NN) interval (ms) (cont'd)	Psychological or mental stress (cont'd)	Able to differentiate between the stressful and the non-stressful conditions [27]	Paired t-test (non-stress= 94.43 ± 11.67; stress=106.97 ± 13.04; p<0.01)
				Differences between the rest and mental stress these two conditions in the Mensa test [53]	Paired and unpaired t-tests or Mann-Whitney U-tests and Wilcoxon signed-rank test (p<0.05)
				Physiological signal: the most discriminating HRV metrics to differentiate between the stressful and non-stressful conditions Psychological stress: shows positive/negative correlation with psychological stress test using STAI [41]	Physiological signal: One-way ANOVA (p < 0.0001) and Tukey multiple comparison test (p < 0.05) Psychological stress: Wilcoxon Signed Rank test (not signif-icant)
				Decreased for increased stress and able to consistently differentiate the high and the low stress levels [48]	Absolute reliability: Mean difference Relative reliability: Kendall's tau Between conditions: Paired t-test or Wilcoxon rank sum test
			Physical fatigue or pain	Electric pain: Pain significantly decreased during rest, during attention to pain [46]	Two-Way RMANOVA (Music= 1020 ±127 vs. Rest = 879 ±119 (p<0.001); Rest= 980 ±115 vs. Attention= 873± 127 (p<0.001)
			Not related	Able to differentiate supine and standing these two postures, but not sitting [45]	One-way ANOVA (not significant)
	Mean HR	Mean heart-rate	Psychological or mental stress	Able to differentiate between the stressful and the non-stressful conditions [27]	Paired t-test (non-stress= 0.042 ± 0.012; stress=0.033 ± 0.009; p<0.01)
Frequency domain param-eters	LF	Low frequency of the heart rate, range .04 to .15 Hz (ms2)	Psychological or mental stress	Significantly affected by mental stress with PASAT as the stimulus [46]	Two-Way RMANOVA (Rest =1542 ± 1492 vs. PASAT=867 ±862 (p<0.01))
			Physical fatigue or pain	Electric pain: Increased during pain stimulation from rest. [46]	Two-Way RMANOVA (Rest= 1645 ±1416 vs. Pain = 2089 ±1451 (p=0.02))
				Decreased while observing physical fatigue at the workplace [54]	Two-factor ANOVA (–22.2%, p<0.01)
				Increased when shown signs of fatigue (tired eyes, prolonged eye closure, and head nodding) or after 2 hours of driving [55]	One-way ANOVA
			Not related	Able to differentiate supine and standing these two postures, but not sitting [45]	One-way ANOVA (not significant)
	HF	High frequency of the heart rate, range .15 to .40 Hz (ms2)	Psychological or mental stress	Changed significantly during stress [49]	Meta-analysis
			Physical fatigue or pain	Decrease while observing physical fatigue at the workplace [54]	Two-factor ANOVA (–33.3%, p<0.05)
			Not related	Not affected by fatigue [55]	One-way ANOVA
	LF/HF Ratio	Ratio of LF/HF	Psychological or mental stress	Can differentiate conditions related to emotion & empathy [20]	ANOVA (r=-.69, p<0.05)
				Able to differentiate between the stressful and the non-stressful conditions [27]	Paired t-test (non-stress= 1.94 ± 0.095; stress=2.4 ±1.39; p<0.05)

Table 2. HRV parameters and related physiological or psychological phenomena as described in the literature (cont'd)

HRV parameter	Abbreviation	Metric	Relationships	Measures – human responses (e.g. stress) based on literature	Statistics
Frequency domain parameters (cont'd)	LF/HF Ratio (cont'd)	Ratio of LF/HF (cont'd)	Psychological or mental stress	Changed significantly during stress [49]	Meta-analysis
			Physical fatigue or pain	Detect the impact of using compression stockings during prolonged sitting [57]	Two-way repeated-measures ANOVA
				Increased significantly with the running exercise compared to those recorded after rest and recovery nights [58]	Friedman test ($p<0.05$)
				Significant increase when shown signs of fatigue (tired eyes, prolonged eye closure, and head nodding) or after 2 hours of driving [55]	One-way ANOVA
			Time	Significant changes over time [8]	One-way repeated measures ANCOVA ($p<0.01$)
			Not related	Not significant to stress [18]	MANOVA (not significant)
				Able to differentiate between the posture supine and standing, but not sitting [45]	One-way ANOVA (not significant)
	LF norm	Normalized LF (nu)	Psychological or mental stress	Increased for increased stress and able to consistently differentiate the high and the low stress levels [48]	Absolute reliability: Mean difference Relative reliability: Kendall's tau Between conditions: paired t-test or Wilcoxon rank sum test
			Physical fatigue or pain	Increased significantly with the running exercise compared to those recorded after rest and recovery nights [58]	Friedman (Competition. rest and recovery nights are 62.1 ± 15.2 and 66.9 ± 11.6 vs. 76.0 ± 10.7; $p<0.05$ respectively)
				Increased when shown signs of fatigue (tired eyes, prolonged eye closure, and head nodding) or after 2 hours of driving [55]	One-way ANOVA
			Not related	Could not differentiate between the stressful and the non-stressful conditions [27]	Paired t-test (not significant)
	HF norm	Normalized HF (nu)	Psychological or mental stress	Used to classify different levels of stress [59]	
				Could not differentiate between the stressful and the non-stressful conditions [27]	Paired t-test (not significant)
				Decreased for increased stress and able to consistently differentiate the high and the low stress levels [48]	Absolute reliability: Mean difference Relative reliability: Kendall's tau Between conditions: paired t-test or Wilcoxon rank sum test
			Physical fatigue or pain	Decreased significantly with the running exercise compared to those recorded after rest and recovery nights [58]	Friedman (Competition. rest and recovery nights are 37.9 ± 15.2 and 33.1 ± 11.6 vs. 24.0 ± 10.7; $p<0.05$ respectively)
				Decreased while showing signs of fatigue (tired eyes, prolonged eye closure, and head nodding) or after 2 hours of driving [55]	One-way ANOVA

Table 2. HRV parameters and related physiological or psychological phenomena as described in the literature (cont'd)

HRV parameter	Abbreviation	Metric	Relationships	Measures – human responses (e.g. stress) based on literature	Statistics
Non-linear domain parameters	CSI	Cardiac Sympathetic Index	Psychological or mental stress	Able to differentiate between the stressful and the non-stressful conditions [27]	Paired t-test (non-stress= 2.76 ± 0.79; stress=3.56 ± 0.78; p<0.01)
	CVI	Cardiac Vagal Index	Physical fatigue or pain	Reduced during exercise and returned toward resting levels at the end of a recovery period [29]	Two-way ANOVA
			Not related	Could not differentiate between the stressful and the non-stressful conditions [27]	Paired t-test (not significant)
	SD1	Standard deviation of projection of the Poincaré plot on the line perpendicular to the line of identity (ms)	Physical fatigue or pain	Decreased with upright posture, and further decreased during exercise, this could assess the parasympathetic changes induced by short- and/or long-term endurance training [25]	One-way ANOVA and Tukey honest test or paired t-test
				Reduced during exercise and returned toward resting levels at the end of the recovery period [29]	Two-way ANOVA
	SD2	Standard deviation of the projection of the Poincaré plot along the line of identity (ms)	Physical fatigue or pain	Increased during standing and decreased during exercise compared to the supine rest condition [25]	One-way ANOVA and Tukey honest test or paired t-test.
				Reduced during exercise and returned toward resting levels at the end of the recovery period [29]	Two-way ANOVA
	SD2/SD1 Ratio	Ratio of SD2/SD1	Physical fatigue or pain	When standing, decreased significantly which highlights the parasympathetic withdrawal that occurred during standing [25]	One-way ANOVA and Tukey honest test or paired t-test

Objective measurement

The HRV parameters for each seat size are presented in Table 3. Seat 17-28 had the lowest mean values compared with the other seat sizes for parameter SDNN, SDSD, pNN50, pNN20, RMSSD, Mean NN, LF, CSI, CVI, SD1, SD2, and SD2/SD1 Ratio. This result differs from the subjective assessments in Figure 3 where 17-30 was rated the lowest in comfort and highest in discomfort. The average values for 17-30 of HF, LF/HF ratio and LF norm were the lowest compared to the other seat sizes. For SDNN, SDSD, pNN50, RMSSD, Mean NN, LF, LF/HF ratio, LF norm, CSI, CVI, SD1, SD2, and SD2/SD1 Ratio, the 18-28 seat had the highest mean score.

The recorded HRV parameters were also analyzed in time. Each HRV measure was analyzed in a 5-minute window, then these values were averaged for each 15-minutes time frame for all participants. A Pearson's correlation analysis was conducted to identify the relations between the scores of subjective comfort and discomfort over time was correlated to the averaged measures of the HRV at that timestamp (see Figure 4).

Relations among measures

The HRV parameters were computed with a 5-minute interval and averaged for a 15-minute window to identify the correlations between HRV parameters and the comfort/discomfort scores for the corresponding time as shown in Table 5. The Pearson's correlation coefficients were calculated between the mean of the HRV parameters in consecutive 3 intervals (5 minutes each) and the corresponding comfort/discomfort questionnaire scores (15 minutes each). The results indicate that almost all parameters of HRV, except Mean NN and Mean HR, were significantly correlated to the comfort ratings gathered with the questionnaires. The discomfort had the highest correlation with the LF norm and HF norm even though the correlations were not strong.

Table 3. HRV parameters averaged per seat size

HRV parameters		17-28	17-30	18-28	18-30
Time domain parameters	SDNN	56	89	105	78
	SDSD	47	64	75	60
	pNN50	27	44	46	38
	pNN20	61	76	71	66
	RMSSD	47	64	75	60
	Mean NN	723	770	811	732
	Mean HR	82	79	76	85
Frequency domain parameters	LF	1,169	1,680	5,125	2,456
	HF	632	1,270	1,954	1,441
	LF/HF ratio	1.5	1.3	2.2	1.4
	LF norm	55	54	61	54
	HF norm	44	46	39	46
Non-linear domain parameters	CSI	2.1	2.5	2.6	2.4
	CVI	4.5	4.9	5.0	4.7
	SD1	34	46	53	42
	SD2	72	116	138	101
	SD2/SD1 Ratio	2.1	2.5	2.6	2.4

Table 4. Pearson's Correlation of HRV parameters and the subjective comfort and discomfort score at the corresponding timestamp (* p<0.05, **p<0.01)

HRV parameters		Discomfort over time	Comfort over time
Time domain parameters	SDNN	.863**	-.817*
	SDSD	.927**	-.887**
	pNN50	.938**	-.954**
	pNN20	.914**	-.929**
	RMSSD	.927**	-.887**
	Mean NN	-.408	.526
	Mean HR	-.346	.503
Frequency domain parameters	LF	.662	.697
	HF	.855**	.846**
	LF/HF Ratio	.803*	.754*
	LF norm	.817*	.788*
	HF norm	.596	.457
Non-linear domain parameters	CSI	-.898**	.918**
	CVI	.111	.030
	SD1	.928**	-.888**
	SD2	.843**	-.797*
	SD2/SD1 Ratio	-.898**	.918**

Table 5. Pearson's correlation of HRV parameters to subjective comfort and subjective discomfort (* p<0.05, **p<0.01)

HRV parameters		Comfort	Discomfort
Time domain parameters	SDNN	-.505**	.223**
	SDSD	-.408**	.087
	pNN50	-.411**	.074
	pNN20	-.364**	.061
	RMSSD	-.408**	.087
	Mean NN	.033	-.189**
	Mean HR	.037	.167*
Frequency domain parameters	LF	-.436**	.267**
	HF	-.496**	.282**
	LF/HF Ratio	-.193**	.112
	LF norm	-.286**	.133*
	HF norm	.310**	-.160*
Non-linear domain parameters	CSI	-.209**	.156*
	CVI	-.382**	.091
	SD1	-.408**	.087
	SD2	-.510*	.234**
	SD2/SD1 Ratio	-.209**	.156*

Discussions

Comfort/discomfort over time

The subjective comfort and discomfort experiences of passengers were measured over time during a 2-hour session using different types of seats. It was found that discomfort increased over time, while comfort was almost constant in time. Comparing comfort and discomfort to the HRV parameters over time showed a strong correlation between both comfort and discomfort on one side and for the HRV parameters on the other side. This shows that heart rate parameters can be used as an indicator of comfort as well as discomfort.

The HRV parameters that are positively correlated with the subjective ratings at each timestamp were SDNN, SDSD, pNN50, pNN20, RMSSD, HF, LF/HF ratio, LF norm, SD1 and SD2. Meanwhile, a negative relation was found for CSI and SD2/SD1 ratio. Mean NN, Mean HR, LF, HF norm and CVI did not correlate with the subjective rating at that timestamp.

LF/HF ratio was not found to increase over time, which differs from the findings of Le and Marras [8], who reported an increasing trend in the LF/HF ratio of the HRV over time in a 1-hour study, though the trend was low for seated conditions. On the other hand Liu [18] found in a 10-hour study on airplane passengers, that the LF/HF ratio did not change over time. Changes in HRV over time were also not found while doing mindfulness meditation even though participants reported an increase in all measures of well-being [61]. The conditions in this study were seated positions in an airplane seat, which could explain the absence of LF/HF ratio change over time. Eilebrecht et al. [62] explained that the time dependence of HRV parameters is not straight-forward, because it reacts slower to non-instantaneous impulse (e.g. stress) which may cause a delay in the response of the HRV parameters.

The drop at the end of the experiment for discomfort and rise in comfort might be due to the effect that comfort usually increases near the end. At the end of a working week or at the end of a flight comfort increases while the same activity is done due to the fact that the human looks forward to the nice period that is coming [63]. Participants were told that the experiment was 2-hours and ended with a landing position and was aware that were 'freed'.

Comfort and discomfort among seat sizes

Comfort and discomfort results from the questionnaire show that the 18-30 seat had the highest comfort and the lowest discomfort. It seems logical since people will feel more comfortable with the increase of their personal space. On the other hand, we found that the 17-28 seat scored higher in comfort and lower in discomfort compared to the 17-30 seat. Anjani et al. [64] found that the shorter pitch resulted in a lower comfort and higher discomfort, which differed from the results of this study. This might be due to the longer duration of sitting and the use of a tray table for working on a laptop and eating. The horizontal distance between the tray table and the seat was not adjustable, so the participant might bend forward more during these two tasks. This conclusion is in accordance with the literature which indicated that a non-adjustable tray table will decrease comfort if placed too far [65]. Figure 7 shows the changes in discomfort in the last half of the experiment where the participants were not allowed to use the tray table. The measurements of 17-28 and 17-30 are similar in this situation, which might indicate the effect of the distance of the tray table on comfort.

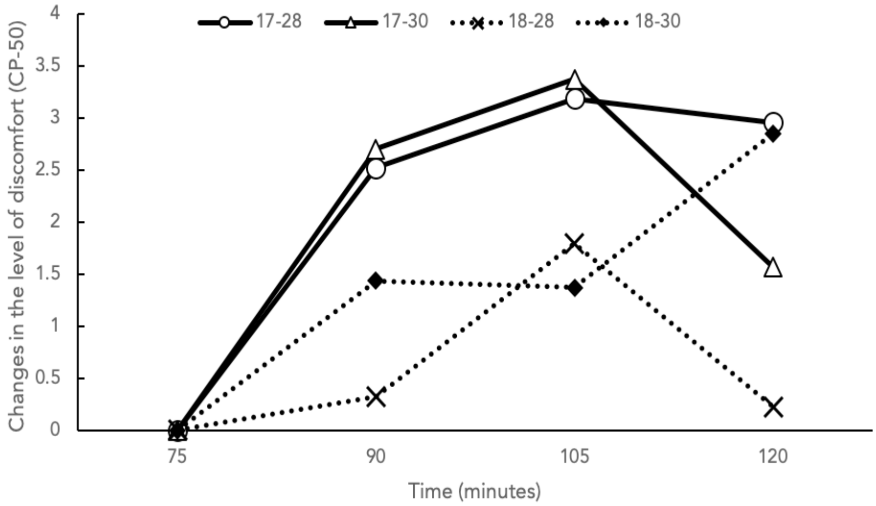

Figure 7. Changes of discomfort level without the use of tray tables

Weston et al. [10] showed that the LF/HF ratio of the HRV was sensitive enough to differentiate between chairs. This study compared 4 different seat sizes and measured the LF/HF ratio for each seat. However, we did not find that the LF/HF ratio changed with different seat sizes. The highest value for LF/HF ratio was found for 17-30 and the lowest for 18-28 which is not in line with the seat space and furthermore, it was also not linked to the subjective assessments made by the participants.

The effect of snack/drink

The discomfort over time (Figure 4) shows a decrease of discomfort after snack/drink time, which was in line with the finding providing food significantly lowered the discomfort of the passengers [66]. Moreover, providing snacks and drinks triggered positive emotions, and also distracts passengers from boredom and the discomfort of lack of legroom [67]. This might show the need for having service interruptions to slightly decrease passenger comfort during a long journey. It is worth noting that the drink provided was non-caffeinated since some research indicated that caffeine can change heart rhythm [68]. Ideally, it would be better if no drinks are served during this experiment to prevent disturbance. However, we asked participants for four times 2 hour sitting and the whole experiment took more time because of preparations. Ethically, we thought it was better to serve drinks.

Parameters of HRV

All parameters of the HRV were extracted and correlated with the comfort and discomfort data from the questionnaire. Almost all parameters, except Mean NN, and Mean HR was correlated significantly with comfort. Meanwhile, there were fewer correlations between HRV parameters and discomfort.

Time-domain parameters

Results of this study show that most of the time domain parameters of the HRV are correlated with comfort. SDNN was found to be negatively correlated with comfort ($r=-.505$, $p<0.01$) and weakly correlated with discomfort reported ($r=.223$, $p<0.01$). Another study reports that SDNN was affected by the levels of stress [27, 41], which might connect to the rather high negative correlation with comfort. Two studies mentioned that SDNN is not correlated to fatigue or pain [45, 46], which might explain the weak correlation between SDNN and discomfort.

SDSD was found to be correlated with comfort ($r=.408$, $p<0.01$). SDSD was found previously as an indicator for the levels of stress [47, 48]. Perhaps there is a relationship between comfort and stress. Nkurikyeyezu [16] mentioned that SDSD could predict thermal comfort, which is in line with this study. SDSD was also used as an indicator of fatigue by trained swimmers [42]. This study did not find a relation between discomfort and SDSD, which might be caused by the absence of physical exercise.

pNN50 is a parameter of the HRV that is used to indicate stress [15], which is proved by several stress measurements in different conditions using the Stroop test, State-trait anxiety inventory (STAI), work stressor index (job stress questionnaire), medical students' stress questionnaire, reported stress of children, perceived stress questionnaire and physical-mental task [27, 49–52, 69–74]. This study showed a correlation between pNN50 and subjective comfort, but not to discomfort, which might again indicate that stress and comfort are related.

Trimmel [52] showed that pNN10 - pNN40 correlate negatively with stress and depression and positively with well-being. pNN20 could also differentiate between stressed and non-stressed conditions [41]. This study found a negative correlation between pNN50 ($r=-.41$, $p<0.01$) and pNN20. ($r=-.364$, $p<0.01$) with comfort but not with discomfort. This again might indicate a connection between stress and comfort. A study done by Jiang et al. [56] showed that pNN20 was associated with the intensity of electrical pain which lasted for 3-5 seconds, but recovered during the ongoing stimulus. This study is a 2-hour study without any noticeable pain stimulus (e.g. defined pressure points, extensive exercise, etc.), so the effects of discomfort might not be distinct.

RMSSD is an often used parameter of HRV that is less affected by respiration and is influenced by the parasympathetic nervous system (PNS) [11]. RMSSD is also recommended as a predictor of short-term parameters of HRV [60]. The present study found that the RMSSD correlates significantly to comfort ($r=-.408$, $p<0.01$), but not to discomfort ($r=.087$, not significant). The study of Beggiato et al. [14] showed that this parameter could measure how participants react to an uncomfortable sensation induced by the experiment. Stress is also a factor that is found to change the values of RMSSD [27, 49]. RMSSD was also found to be significantly more sensitive to the decrease in temperature [75].

The results of this study showed that mean NN had a significant negative correlation with subjective discomfort, though it was weak ($r=-.189$, $p<0.01$). Terkelsen et al. [46] found that the mean NN significantly decreased during electric pain stimulation, attention to pain, as well as mental stress. Moreover, other research found that mean NN was related to physiological stress but not to psychological stress [27, 41], the relationship to comfort in this study was also not present. This could indicate that mean NN is more related to physiological stress or pain, both might be the constructs of discomfort.

Mean HR did not correlate strongly to both comfort ($r=.037$, not significant) and discomfort. ($r=.167$, $p<0.05$). The values did not change over time and did not correlate with the assessments over time. Though some literature indicated that the mean HR can differentiate levels of stress [27].

Frequency domain parameters

Frequency domain measurements of the HRV divides the components based on its rhythms that operate within different frequency ranges [11]. The LF, HF, LF/HF Ratio, normalized LF and normalized HF were calculated in the present study. VLF was not included because this study used short-term recordings [60].

LF was found to have a negative correlation to comfort (r=-.436, p<0.01) and positively to discomfort (r=.267, p<0.01). A study by Terkelsen et al. [46] found that LF increased during electric pain stimulation and also decreased during mental stress stimulation. This negative relation was found in comfort, which is probably related to stress. HF is probably more connected to the activity of the parasympathetic nervous system (PNS). Therefore, a lower HF power is correlated with stress, panic, anxiety, or worry [11, 49]. HF was found to be negatively correlated to comfort (r=-,496, p<0.01) and also correlated weakly to subjective discomfort (r=.282, p<0.01). Again, stress might be more connected to comfort explaining the difference.

The LF/HF ratio is often used in comfort related research. This study found that the LF/HF ratio correlated weakly with comfort (r=-.193, p<0.01), but not with discomfort (r=.113, not significant). In other studies, different results were reported regarding this parameter. The LF/HF ratio was significantly different between standing and perching in adults and children, while it was low or not significant in seated conditions [8, 45]. Weston et al. [10] showed that the HRV can be used to differentiate between chairs, though this study did not find a significant difference between seats. Concerning wearing compression stockings it was found that the heart rate was significantly greater without than with stockings in a prolonged sitting [57]. Thermal changes could also be detected through monitoring the LF/HF ratio, though it was not linked to thermal comfort [7, 19, 75]. Moreover, Pigliautile et al. [76] found that it was better to study other HRV parameters than the LF/HF ratio to determine human thermal comfort. Some studies showed that the LF/HF ratio was not a good indicator of stress, but it could differentiate between emotions and empathy [18, 20]. In the present study, comfort was correlated with the LF/HF ratio, which might be driven by emotion and empathy, as in the experiment the temperature was kept constant and participants were asked to stay seated during the 2-hour session.

A normalized LF and HF were also analyzed in this study. This is done because normalization removes most of the large across-subject variability in the total raw HRV spectrum [77]. It was found that the LF norm was weakly correlated to subjective comfort (r=-.286, p<0.01), and subjective discomfort (r=.133, p<0.05). While HF norm was only found to be correlated weakly to discomfort (r=-.160, p<0.05). A study done by Tanev et al. [59] used HF norm to classify stress. However, another study by Yang et al. [27] was not able to differentiate stressed and non-stressed conditions using the LF norm and the HF norm.

<u>Non-linear parameters</u>
The present study extracted the nonlinear parameters of the HRV and compared it with comfort and discomfort. The nonlinear methods might elicit valuable information for physiological interpretation of HRV, though standards and interpretation methods are lacking [60].

Yang et al. [27] found that CSI can differentiate stressed and non-stressed conditions, whilst CVI could not. This study found a weak relationship of CSI (r=-.209, p<0.01) and CVI (r=-.382, p<0.01) to subjective comfort. Moreover, CVI was found not to correlate to time, nor to subjective comfort and discomfort over time. Macartney et al. [29] found that CVI reduced during exercise and returned at the end of the recovery period, this might indicate that the CVI will stay at a similar level if there is no physical exercise done.

The present study showed a correlation between SD1 (r=-.408, p<0.01) and SD2 with comfort (r=-.510, p<0.05) and also between SD2 and discomfort (r=.234, p<0.01). Gadea et al. [30] extracted SD1 and SD2 and compared them to discomfort ratings, and they did not find correlations. Tang [78] presented the results of SD1 and SD2 in the evaluation of mental stress during cognitive activities and found that in the results of a participant the SD1 and SD2 decreased during the activity, though no statistical analysis was done. Melillo [23] classified it as stress when the SD2 is higher than 64.6ms, though this indicator could only be used if there is no change in posture, which was not restricted in the present study. SD1 and SD2 appeared also to be related to fatigue during exercise [25, 29], which was also not the case in the present study.

Mikuckas et al. [79] did a study on emotion recognition and found that nonlinear parameters depended more on the physical load than on the emotional state. This study only found correlations between discomfort and SD2 (r=.234, $p<0.01$) and CSI (r=.165, $p<0.05$). Other parameters were correlated to comfort. It is worth noting that in this study there was no physical loading or exercise during sitting, which could be the cause of the weak relation with fatigue.

In summary, this study showed that some HRV parameters are linked to comfort and discomfort while sitting in an economy class aircraft seat. The SDNN, LF, HF and SD2 showed the strongest correlation with comfort as well as discomfort. LF did not correlate well with the subjective assessment in the corresponding timestamp, which might indicate that LF is not a good fit for long studies. These parameters might indicate the presence of comfort and discomfort of participants while sitting in an economy class seat in an airplane.

Conclusion

A 2-hour study was done on different economy class seat sizes to show the effect of comfort and discomfort over time. Participants sat in two different seat pitches (28 inches and 30 inches) and two different seat widths (17 inches and 18 inches) while having their heart rate monitored. Questionnaires that measure subjective comfort and subjective discomfort were collected every 15 minutes. Results show that the 18-inch-wide and 30-inch-pitch seat with the largest seat space performed the best in comfort and had the lowest discomfort. Though the seat with the least space did not perform the worst, probably the presence of a tray table might have had an effect on comfort and discomfort. Similar to the subjective assessment, HRV parameters did not change with the increase of seat size. It shows that small differences in size do not have a significant effect on HRV parameters. However, in time many HRV parameters were linked to comfort. This study indicates that for future research SDNN, HF and SD2 might be interesting parameters to apply because they have the best correlation to subjective comfort and discomfort and could indicate the changes over time.

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CHAPTER 4

Perceived Effects

This chapter is is based on:

Anjani S, Kühne M, Naddeo A, Frohriep S, Mansfield N, Song Y, Vink P (2021).
PCQ: Preferred Comfort Questionnaires for Product Design.
Work 68:s1. https://doi.org/10.3233/WOR-208002

PCQ: Preferred Comfort Questionnaires for Product Design

Abstract

Selecting a proper questionnaire(s) in comfort research for product design is always a challenge, even for experienced researchers. The objective of this research is to propose a list of PCQ: Preferred Comfort Questionnaires for product/service design to help researchers in the selection of questionnaires for comfort research. Fifteen questionnaires which were often used in comfort research for product design were selected as candidate questionnaires. During the Second International Comfort Congress (ICC 2019), 55 comfort researchers joined together in a workshop to rate these questionnaires individually as well as rank them in groups based on their experience. The criteria of rating and ranking included easiness to answer, easiness for data interpretation, the time needed to complete, the needed prior training, as well as the suitable design phases and fields of application. Answers of individual feedback regarding each questionnaire were collected, analyzed and synthesized with the choices of groups. For comfort research in the proposed five application fields and four design phases, the preferred questionnaires were highlighted and categorized into four categories: preferred questionnaire, suitable for less prior training, suitable for fast completion and generally applicable, which led to a list of PCQ for Product Design. We expect that the PCQ list can be used as a useful instrument to help researchers in the initial selection of questionnaires for comfort research in product/service design.

Introduction

The need for comfort is common for all people across different stages of their life [1]. However, comfort is an individual and subjective concept, and it depends on the personal experience and the physiological, physical, mental, emotional and social state of the person over time. This individual and subjective concept of comfort are important in product design. Dimensions of product design, such as the user, the product and the context will interact with each other over time and contribute to the perception of comfort.

Vink and Hallbeck [2] defined comfort as “a pleasant state or relaxed feeling of a human being in reaction to its environment” and discomfort as “an unpleasant state of the human body in reaction to its physical environment”. These definitions clarified the difference between comfort and discomfort, and also highlighted the importance of the subjective aspects of comfort. Therefore, in the evaluation of users’ feeling of comfort/discomfort over time, in addition to objective measures such as posture (changes), the pressure distribution of different parts of the body and/or physiological measures, questionnaires have been, and will continue to, be important research instruments.

In the past decades, researchers developed many types of questionnaires, and they were proven to be useful instruments in evaluating the subjective feeling of people in comfort studies applied to diverse fields. Examples of those questionnaires are hand map discomfort [3], CP50 [4], Localised Postural Discomfort (LPD) [5], etc. New application fields continuously emerge and the requirements/constraints are different in each application. Questions such as “What is the cost of each questionnaire regarding time and the effort of the participants?”, “Which one is more suitable for a given design phase?”, “What is the most suitable questionnaire for evaluating the use of a particular product?” often appear in the planning of comfort research. In most cases, the selection of the questionnaire(s) is strongly based on the experience of the researchers.

In the Second International Comfort Congress 2019 (ICC 2019 [6]), comfort researchers and practitioners from around the world joined together in a workshop to create an instrument for questionnaire selection. The outcome of the workshop is the list of PCQ (Preferred Comfort Questionnaires) for Product Design. It is expected that this list will facilitate researchers in selecting the most suitable questionnaire(s) considering different requirements/constraints in comfort studies, especially at the research planning stage.

In this paper, we describe the selected candidate questionnaires, the setup of the workshop, and the data processing method in the Materials & Methods section. The workshop results are presented regarding the perceived characteristics of each questionnaire, the preferred application field, and the most appropriate stage of the product design progress. Characteristics and categorizations of the questionnaires and the usage of them are discussed. Finally, based on the synthesis of the results, we propose the list of PCQ for product design.

Materials & Methods

Based on a review of the literature on the topic of comfort in product design, and with the advice of experts on both design research and design applications, 15 candidate questionnaires were identified and used as the basis of the research. Table 1 lists the type of questionnaire and the characteristics of each questionnaire regarding visual representations, number of questions, type of scales, scale range, and statistical/analysis method.

The use of scales in formulating the questionnaires varies among questionnaires. Some opt for a numeric rating scale (NRS), others chose a graphical rating scale (GRS) or a verbal descriptor scale (VDS) with text. An NRS is defined as a set of numbers and an anchored endpoint, where these anchors serve as reference points for the participants [23]. A GRS is a visual analogue scale (VAS) with verbal anchors positioned on the line. The user can use GRS to report body sensations which is harder to describe by using a basic VAS [24]. VDS is a scale comprising verbal descriptors which have been found to be capable of, for example, capturing the intensity of pain and was preferred by older participants [25]. The scale range also differs among questionnaires. Preston and Colman [26] recommended the use of 7, 9, or 10 response categories for questionnaires, as fewer categories result in lower reliability (stability), internal consistency, validity, discriminating power and respondent's preference. Moreover, the reliability also decreases for scales using more than 10 categories. Researchers may consider the target group especially the context, the grading system and the mother language when specifying the type and range of scales of the questionnaire.

Most of the candidate questionnaires are 1-stage questionnaires except Questionnaire 3 (CP50), 14 (Mansfield's two-stage method) and 15 (Auditory comfort), which have two stages and the first question is often used as a priming question. Tulving and Schacter [27] defined priming as a "nonconscious form of human memory, which is concerned with perceptual identification of words and objects and which has only recently been recognized as separate from other forms of memory or memory systems." The priming effect increases the accessibility of the information relevant to the question [28], and therefore influences the choice of response alternatives for the upcoming question [29]. Questions with priming attempt to steer the cognitive processes prior to the main question in an attempt to improve repeatability, and to minimize the cognitive processing needed to answer it [29].

Fifty-five participants of ICC 2019 conference joined the workshop and they were randomly assigned to one of 3 studios. For each studio, participants were clustered into 3 or 4 groups with 5 or 6 members, depending on the actual number of participants. The workshop was executed in two phases: an individual evaluation phase and a group discussion phase, each approximately 40 minutes long. In the individual evaluation phase, each group divided 15 questionnaires among the group members, so each participant analyzed 3 questionnaires regarding 1) Experience with the questionnaire, 2) Easiness to answer, 3) Easiness for data interpretation, 4) Estimate of the time needed to complete the questionnaire, 5) In which stage of the experimental study the questionnaire is recommended, 6) The need for participant training prior to the experiment, and 7) Which design phase the questionnaire belongs to. Participants were also able to add extra comments and they were encouraged to propose relevant questionnaires that were not on the list.

Table 1. Candidate questionnaires and their characteristics

No.	Name	Visual representations	Number of questions	Type of scales	Scale range	Analysis method
1	Hand map discomfort [3, 7]	Image	13	NRS-fully anchored	0 (no discomfort) - 5 (extreme discomfort)	ANOVA; Spearman; Friedman
2	Seat elements questionnaire [8]	Text	11	NRS- end anchored	0 (dislike) - 9 (like)	Wilcoxon test
3	CP50 [4]	Text	1 (2 stages)	Stage 1; GRS; Stage 2: NRS	0 (very light discomfort)-52 (exceeding very severe discomfort)	Linear = t-test; quadratic = F-test
4	Localised Postural Discomfort (LPD) [5]	Image	19	NRS-fully anchored	0 (no discomfort) - 10 (extreme discomfort)	Wilcoxon
5	Green red body map [9]	Image	22	Colors (red green)	red= discomfort, green= comfort	
6	Task specific comfort [10, 11]	Text	25	NRS-fully anchored	Varies	Pearson
7	Simple comfort score [12, 13].	Text	2	NRS-end anchored	0 (no discomfort) - 10 (extreme discomfort) and 0 (no comfort) - 10 (extreme comfort)	Wilcoxon; t-test
8	Postural comfort (joint and segments) [14]	Text	1	NRS- end anchored	-1 - 10 (comfort)	Statistical distribution
9	Body region discomfort [7]	Image	12	NRS-end anchored	1 (extremely comfortable) - 7 (extremely uncomfortable)	
10	Modified ASHRAE thermal comfort [15, 16]	Text	14	NRS-fully anchored	0 (very hot with excessive discomfort) - 3 (neither hot nor cold comfort) - 0 (cold with excessive discomfort)	Pearson
11	Modified SAE for reachability [17]	Text	1	VDS	1 (high) - 10 (none)	Correlation index
12	Modified Body region Discomfort [18]	Image	25	NRS-end anchored	1 (no discomfort)-10 (extreme discomfort)	T-test
13	Multi factorial methods – cross modal matching ISO 20882 [19]	Text	19	GRS		
14	Mansfield's two-stage method [20, 21]	Image	No. 1: 5; No. 2: 1(2-stages)	No. 1: NRS-fully anchored; No. 2: stage 1: GRS; stage 2: NRS	No.1: 1 (not uncomfortable) - 6 (extremely uncomfortable); No. 2: 0 (no discomfort at all) - >120 absolute maximum	T-test
15	Auditory comfort [22]	Text	1 (2-stages)	Stage 1: VDS	Stage 2: NRS-end anchored	0 (not at all) - 10 (extremely)

After the individual phase, participants discussed with their group the preferred questionnaire(s) regarding design phases and different application fields. The design phases included: 1) Early design phase; 2) Studying prototypes; 3) Comparing two products/prototypes; and 4) Evaluating the final product; and the application fields were: 1) Hand tool and handle; 2) Feet/leg study; 3) Seat study; 4) Total environment and 5) All sorts of products.

165 individual responses were collected; one record was excluded due to incorrect labelling of a candidate questionnaire. Eleven group responses were collected. In the processing of individual responses, the experience of the participant was used as a weight factor of the scores, i.e. for a given item, its score was normalized as

$$weighted\_item_k = \frac{experience_k \ * item_k}{\sum_{i=1}^{n} experience_i},$$

where k is the index of items and n is the number of participants. For $experience_k$, it was set as 3 for participants who used it before, 2 for participants who knew it and 1 for participants who had no experience with it. All weighted scores are then normalized between 0 and 1 using the MinMaxScaler [30] except two items: "Time to complete the questionnaire?" and "Is training prior to the experiment required?", as the answers to those questions were the estimation of a time scale and Boolean values, respectively.

For the individual phase, each participant was given a printed booklet with all 15 questionnaires and another booklet to complete the survey of the assigned questionnaire and to suggest other recommended questionnaires. The usage context and references were included in the description accompanying each questionnaire. Participants were also supplied with the full reference in a link provided for the workshop. During the group phase, a sheet with a blank table was provided and groups were instructed to write the index of the top 3 questionnaires regarding the suitable design phases in different application fields.

The collected data was digitalized and where necessary, two researchers discussed the answers to avoid misinterpretation of the handwriting. Two researchers independently analysed the data using different tools, i.e. Microsoft Excel and a self-developed Python program. A Pearson correlation using SPSS version 25 was conducted to identify a possible correlation between "Easiness for data interpretation" and "The time needed for finishing the questionnaire". After finishing the individual analysis, two researchers compared the results against each other and in the case of discrepancy between the intermediate results, e.g. a bug in the code, they analyzed and understood the differences and were able to reach a consensus.

Results

Experience of participants

The participants of this study were already working in the field of comfort research and application, so most of them knew some of the questionnaires well. For instance, most participants assigned to Questionnaire 9 knew the questionnaire and the majority had used this before. An exception was Questionnaire 8 and 15, in which no participants had the experience though some participants knew of it (Figure 1).

Usage of questionnaires

Considering the results of "Easiness to answer" and "Easiness for data interpretation" questions it was found that Questionnaire 5, 7, 8, 13 and 15 were among the easiest questionnaires to be answered where Questionnaire 3 and 12 were relatively difficult (Figure 2). Participants of the workshop also indicated that Questionnaire 14 was easy to interpret where Questionnaire 10 and 11 were relatively difficult.

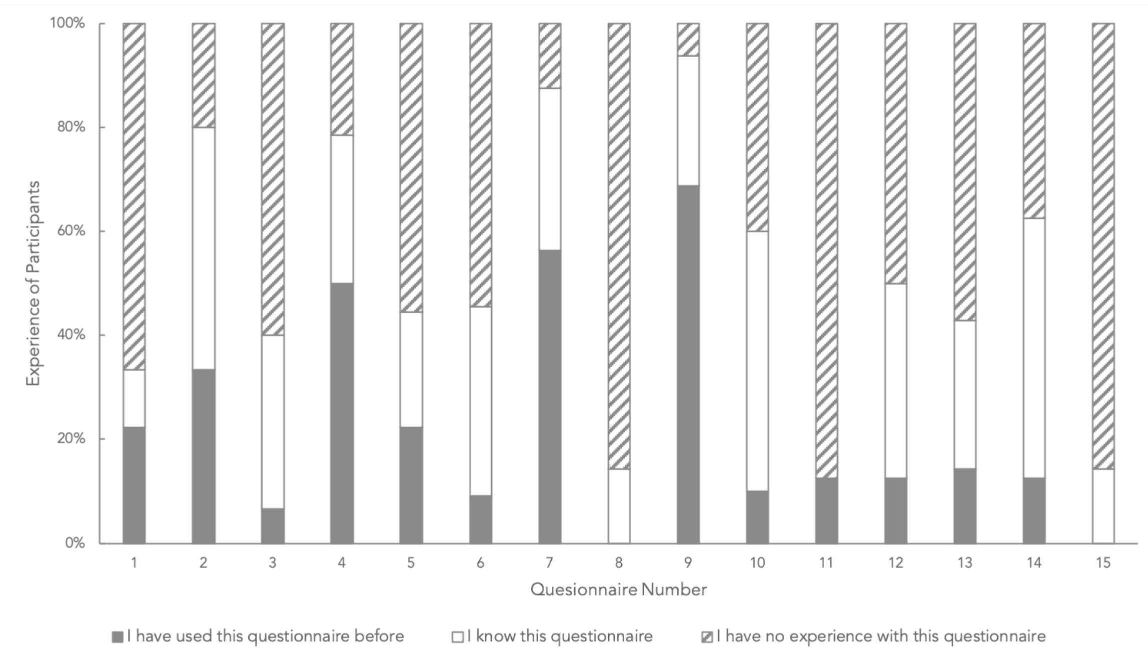

Figure 1. Experience of participants in using the questionnaires

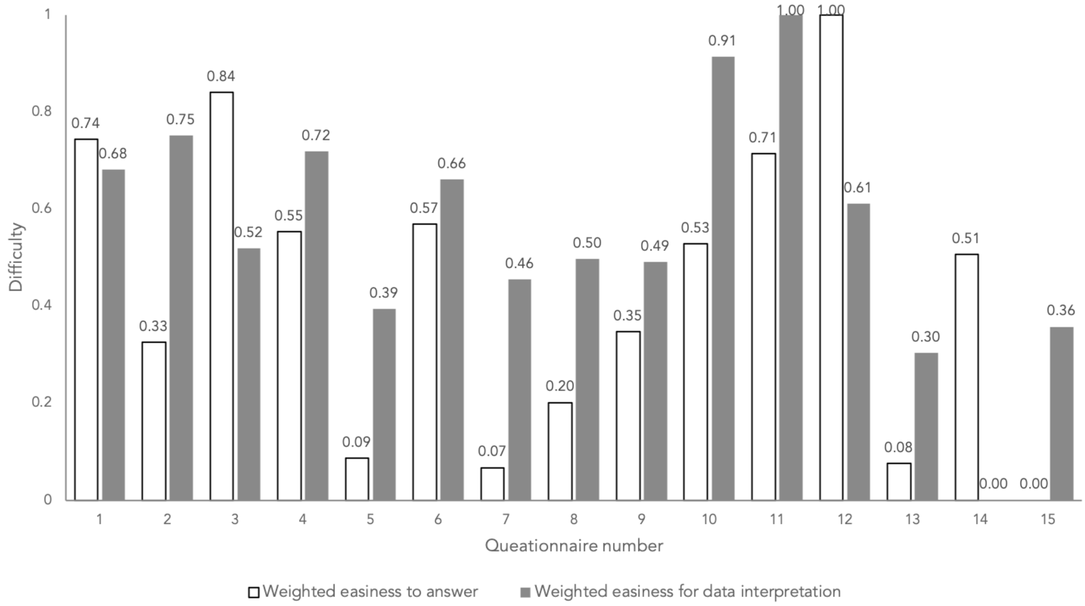

Figure 2. Individual evaluation of questionnaires regarding easiness of answer and easiness of interpretation

Considering the results of "The time needed for completing the questionnaire" and "Is prior training needed?" questions it was found that Questionnaire 7, 11, 14 and 15 required less completion time than others (Figure 3). On the contrary, Questionnaire 1, 6 and 13 took more time. Regarding the question "Is prior training needed?", participants strongly suggested that prior training was needed for Questionnaire 1, 2, 7 and 15, but less for Questionnaire 4, 11 and 12.

Table 2. Results of the choice of groups regarding different design stages and different applications (shaded = >50%)

Phase	Rank	Hand tool and handle		Feet/leg study		Seat study		Total environment		All products	
		Questionnaire No.	Percentage	Questionnaire No.	Percentage	Questionnaire No.	Percentage	Questionnaire No.	Percentage	Questionnaire No.	Percentage
Early design phase	1	1	36%	8	45%	2	55%	7, 15	45%	7	55%
	2	7, 8, 11	18%	1	18%	6	27%	13	36%	3, 5, 15	18%
	3	5, 13, 14	9%	2, 3, 4, 5, 6, 7, 11, 14	9%	3, 4, 5, 7, 14	18%	2	18%	2, 4, 6	9%
Studying prototypes	1	1	82%	9	27%	2	64%	13	64%	3	64%
	2	8, 11	18%	3, 4, 10, 14	18%	9	55%	3, 7, 10, 15	36%	7, 9	36%
	3	2, 3, 6, 10, 13, 14	9%	1, 2, 6, 8	9%	14	45%	4, 6	18%	5, 10	18%
Comparing two products	1	1	82%	8, 9	27%	2, 14	64%	13	64%	3	45%
	2	3	18%	2, 3, 4, 6, 14	18%	9	55%	3, 7	36%	7, 9	36%
	3	2, 4, 5, 7, 8, 9. 10, 11, 14	9%	5, 10	9%	6	45%	10, 15	27%	5, 6	27%
Evaluating an end product	1	1	82%	3	36%	2, 14	55%	13	64%	7	55%
	2	3, 6, 11	18%	9	27%	9	45%	7	45%	3	45%
	3	2, 4, 7, 9, 10, 14	9%	4, 5, 6, 14	18%	3, 6	36%	3, 10, 15	27%	9, 10	27%

Application fields in product design

The questionnaires that were preferred by the groups showed variation across different design stages and different application fields (Table 2). In Table 2, if a questionnaire was recommended by more than 50% of the participating groups, it is highlighted. It can be observed that: 1) For the 'hand tool and handle', 'seat study', and 'total environment', the participating groups' recommendations converged towards one or two questionnaires; 2) the recommendations were relatively diverse and showed less consensus regarding the 'feet/leg study'.

Other recommendations

Besides the selected 15 candidate questionnaires, participants also recommended other questionnaires which might be useful for comfort research. They are: 1) Shoe microclimate evaluation questionnaire [31]; 2) Situation awareness global assessment technique (SAGAT) [32]; 3) Methodologies for subjective evaluations of the indoor environment in ISO 15251 [33]; 4) The scale used in ESI virtual seat solutions (PAM comfort) [34]; 5) the Kano model [35] and 6) Multifactorial assessment of comfort of clothing [36]. It is noted that whilst these questionnaires may be very useful for their targeted applications, they are difficult to apply outside of their application area focus.

Discussion

The validity of the study

Fifty-five participants joined the workshop, each of whom was working in the field of comfort research or application; the expertise of the participants can be reflected in that at least one person knew each questionnaire (Figure 1), despite the fact that the questionnaires were randomly assigned to each participant. Previous studies tried to compare the objectivity between questionnaires without the use of experts [4, 37], however, Olson [38] found that experts can better predict questions with data quality problems and questions leading to inaccurate reporting compared to a computerized question evaluation tool. Research has also indicated that people with similar backgrounds would rate the face validity similarly [39], expert judgement could also determine the face validity which makes sure that a test would not only be valid but also appear valid [40]. Therefore, the 55 experts' opinions can be used as a quality assurance of the outcomes of this study.

Characteristics of questionnaires

Characteristics of a questionnaire may influence its deployment in comfort studies. For instance, if a questionnaire takes a long time to complete, it may be not suitable for comfort studies on the development of comfort/discomfort over time where it needs to be applied multiple times. Training users might also be a problem for large scale studies, e.g. in an experiment of studying the comfort of a product based on visitors in an exhibition, prior training of the participants can be difficult.

Based on the results, it was found that regarding general comfort, Questionnaire 7 Simple comfort score was easy to answer and takes less time to complete for participants with prior training. Therefore, it is suitable for studying comfort over time in a controlled experiment where prior training can be deployed. Questionnaire 5 Green red body map and Questionnaire 15 Auditory comfort have similar characters; however, they will take a bit more time to complete as the number of questions is more. Questionnaire 4 LPD was highlighted as being relatively easy to answer and that little prior training is needed, this makes it suitable for large scale on-site experiments where the participants can just "walk-in" for the experiment.

Statistics show that "The time needed for finishing the questionnaire" was significantly correlated ($p=.006$) with the number of questions of each questionnaire, but has no statistically significant correlations with "Easiness to answer". This shows that respondents would need more processing time to answer many questions, even for questions with a low difficulty level.

Design phases & Application fields

Generally, the narrower the application fields are, the more specific the recommended questionnaires are. For instance, Questionnaire 1 Hand map discomfort was strongly recommended for the application field Hand tool and handle. However, it was found that for application fields All sorts of products, the recommendations of all groups converged towards several candidate questionnaires (3 and 7 in this case). This indicates that Questionnaire 3 CP50 and 7 Simple comfort score are "universal" questionnaires and it can always be a (secondary) choice for different types of comfort studies.

Regarding different design phases, participants found fewer questionnaires were suitable for the Early design phases where Questionnaire 7 was strongly recommended as an instrument to get a holistic view of comfort, though the coefficient of variation was larger showing the participants' opinions differ more. For the remaining design phases, the number of recommended questionnaires were more and the opinions converge more, which were represented by smaller coefficients of variation. Participants suggested that during the study of the prototype and while comparing two products, more detailed examination of comfort was needed, therefore Questionnaires 3, 4, 5 and 6 were often recommended. However, in the final examination of products, Questionnaire 7 Simple comfort score was recommended again to obtain a holistic view of comfort. This holistic view – detail examination – holistic view approach is in accordance with the diverging-converging product design process [41].

Language of questionnaires

Language and its comprehension are important factors to consider during questionnaire design in order to minimize queries, unanswered questions and misinterpretations to resolve [42]. All questionnaires discussed in this study were in English or had been previously translated to English, for example, the Modified Body Region Discomfort questionnaire was originally developed in German and the Postural Comfort questionnaire was originally in Italian. This translation could cause a different understanding, as people from different regions consider the same word at different levels of strength, e.g. Fields et al. [22] compared wording in three English speaking countries (Australia, USA and UK) and they concluded that the perceived intensity of some words varies with region of domicile. The participants of this workshop came from all over the world too, which could have resulted in a different understanding, though none of the participants reported a misunderstanding of the questionnaires provided in the workshop. Greco [43] recommended that the translation is best done by someone well aware of the intent f each question, moreover, the results could then be check by using expert evaluators to evaluate its content, meaning, clarity of expression and comparability to the original item; back-translation; and/or cross-language equivalence.

Scales used in questionnaires

The selection of scale for each question should also be considered by researchers. Annett [44] mentioned that subjective rating scales used in questionnaires are based on the assumption that the human participant normally responds quantitatively to variations in the specified sensory attribute of the stimulus object or situation, therefore the design of these subjective rating scales in the field of comfort varies in terms of the stimuli that the content of the questions may trigger. Cameron [45] conceptualized the tradeoffs between ease of use and precision of measurement in work-related body-part comfort questionnaires. This study shows that binary yes/no options and scales with verbal categories are easy to use with a lower precision, while numerical scales (e.g. CR-10) is harder for participants, but with higher precision. In this study, it was also found that Questionnaire 5 which uses the binary scale and Questionnaire 15 which utilizes the verbal scale are the easiest two. On the other hand, Questionnaire 7 which uses a CR-10 also was also rated as an easy-to-answer questionnaire.

Most comfort questionnaires utilize standard scales or variations thereof e.g. Likert (Questionnaire 2 and 7), Borg (Questionnaire 4, 7 and 14), ISO (Questionnaire 2, 10, 13 and 14) and SAE (Questionnaire 11). Questionnaire 4 and 7 opt for the Borg CR-10 scale, Questionnaire 14 uses the Borg CR-100 scale. The effectiveness and efficiency of the used scales have been discussed in the literature, e.g. Fields et al. [22] compared different options of scales for auditory comfort and they opted for a 5-point verbal scale and a 0-to-10 numerical scale for Questionnaire 15. Scales in CP-50 were also selected based on a comparison with the Borg CR-10 scale, the Corlett discomfort scale, an 8-point ordinal scale, a modified intensity and discomfort scale, and a 21-point ratio regarding the overall reliability and validity for pressure intensity and discomfort ratings [4].

While most questionnaires opt for an NRS which has quantifiable numbers to describe the sense of comfort, Questionnaire 1, 4, 9, 12 and 14 used an image to show the locations of the body part for specifying the location of the stimuli. On the other hand, questionnaires that are not directly linked to specific parts of the body e.g. Questionnaire 2, 3, 6, 7, 10 and 15 chose to use a textual representation paired with an NRS. Another aspect to consider when choosing a scale is the topic and characteristic of respondents. When the topic is relevant to the respondents' context, providing more points may improve the accuracy, but it will cost more time for the users due to the needs for more detailed judgement [46]. On the other hand, having enough points to show the sensitivity of the data is also important, e.g. Questionnaire 6 mostly used a 6-point scale, whilst the author debated whether this scale was long enough to capture the results [10].

Limitations

This research analyzed discussion and comparison of different types of comfort questionnaires in a workshop using a limited number of participants. The questionnaires included were identified by literature study and recommended by experts in the field. Besides other questionnaires recommended by participants, which will be further investigated, there is still a small chance that some alternative questionnaires are still missing. In the future, new questionnaires may come up and the PCQ would need to be updated.

During the workshop, it was found that in the pre-prepared document, Questionnaire 3 had an incorrect image, and Questionnaire 7 had an image of the updated questionnaire instead of the original version. Though most participants reported and corrected the mistake during the workshop based on their own expertise, this might lead to a different understanding of the participants in the individual evaluation.

Table 3. PCQ for Product Design

		Hand tool and handle	Feet/leg study	Seat study	Total environment	All sorts of products
Early design phase	Preferred	1	8	2	7, 15	7
	Less prior training	11	3, 4, 11	3, 4	N/A	3, 4
	Fast completion	7, 8, 11, 14	8, 7, 11, 14	7, 14	7, 15	7, 15
	Generally applicable	5, 13	1, 2, 5, 6	5, 6	2, 13	2, 5, 6
Studying prototypes	Preferred	1	9	2, 9	13	3
	Less prior training	3	3, 4, 11	14	3, 4	3
	Fast completion	8, 11, 14	8, 14	9	7, 15	7, 9
	Generally applicable	2, 6, 10, 13	1, 2, 6, 10	N/A	6, 10	5, 10
Comparing two products	Preferred	1	8, 9	2, 14, 9	13	3
	Less prior training	3, 4	3, 4	N/A	3	3
	Fast completion	7, 8, 9, 11, 14	8, 14	9, 14	7, 15	7, 9
	Generally applicable	2, 5, 10	1, 2, 6, 5, 10	6	N/A	5, 6
Evaluating an end product	Preferred	1	3	2, 14	13	7
	Less prior training	3, 4,	3, 4	3	3, 15	3
	Fast completion	7, 9, 14	9, 14	9, 14	7	7
	Generally applicable	2, 6, 11, 10	5, 6	6	10	9, 10

PCQ for Product Design

Based on the outcomes of the workshop and discussion, we identified the following list of PCQ for Product Design for different application fields regarding different design phases (Table 3). In the Table, beside the preferred questionnaires, we also recommend 1) a set of questionnaires for large scale experiments where training cannot be provided to the participants; 2) a set of questionnaires for fast completion, wherein the experiment, the completion time is a constraint; and 3) a set of questionnaires which can be helpful for this particular application field in the specified design phases.

Conclusion

Selecting proper questionnaires for investigating the comfort of users can be a challenging task, even for experienced researchers and practitioners. In this research, we propose a list of PCQ for Product Design regarding different design phases and application fields, and we expect it can be used as an instrument to help researchers in selecting questionnaires in comfort research. Meanwhile, based on the feedback of the researchers and new research outcomes, we will continue consolidating this list for a better recommendation for researchers in the field of designing for comfort.

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CHAPTER 5

Application

This chapter is based on:

Anjani S, Song Y, Vink P (2021) Designing a floor plan using aircraft seat comfort knowledge by aircraft interior experts. Work 68:s1. https://doi.org/10.3233/WOR-208001

Designing a floor plan using aircraft seat comfort knowledge by aircraft interior experts

Abstract

Recent research indicated that an 18”x30” aircraft seat resulted in nearly the same level of comfort as a 17”x34” seat. However, it took less space in the floor plan. This study explores seat layouts preferred by experts regarding different criteria. Those results of the experts are later compared to layouts produced by computational algorithms to evaluate the advantages of each method. Eighty-eight experts in the field of aircraft interior were invited to make a floor plan of a part of a Boeing 777 aircraft where comfort was one of the main goals. Participants worked in groups of 3 and are given the freedom to design a section of the cabin between economy and first-class (5.87m wide and 3.7m long), where besides these two types of seats, an old business-class size seat of 20”x36” was introduced as well for more flexibilities in design. Computational algorithms were also applied with the same inputs and constraints to generate layouts as a comparison. In total, 29 floor-plans were made, and these plans were analysed to compare against the complexity of the operations, the number of passengers on board, the revenue of the airline, and the width of the aisle. Results showed that 14 groups opted for the economy seats, while the rest utilized a hybrid setup where the business class seats were used in the configuration. These results are compared to the 126 computerized layouts generated. Among all layouts designed by experts, a combination of 28 18”x30” seats and 20 17”x34” seats had the highest potential revenue of US$21,984. This floor plan fits the regulations with an aisle width of 0.93 m. The computerized layout had a better outcome in maximizing profit of US$22,416 with 32 18”x30” seats and 16 20”x36” seats. However, the comfort of such results was to be explored as some seats were rotated 90 degrees.

Keywords: Aircraft Seat, Pitch, Width, Comfort, Layout

Introduction

The airline industry is a competitive market where passengers demand comfort at a low price. Airlines are adding different comfort features in order to be chosen by customers, but they also need to maintain a certain level of revenues for a sustainable business. Therefore, between choices of offering maximum comfort to all passengers and making this an upgrade service feature, most airlines opt for the latter option, especially the low-cost carriers (LCCs) as 1) the fares are low regardless of their service quality; and 2) by adding additional features, LCCs can get a revenue stream of 8-13% from service features [1]. Furthermore, this upgrade feature is also recommended for full-service carriers (FSCs), as it will affect passenger choice by giving an option to increase comfort for passengers who are willing to pay more [2].

Additional seat space is one of the highlighted upgrade features that is offered by airlines. Some airlines choose to provide longer seat pitches throughout their economy class, while others have a special class in between business and economy, usually called premium economy. This class is placed in-between business class and economy with various labels e.g. Premium Economy, Elite Class, Economy Comfort, Economy Comfort, Club Economy, or Premium [3]. Airlines also have various dimensions for their seat space in this class. Lee and Luengo-Prado [4] found that having a larger seat space only for this in-between class more profitable for the airline. This is because not all customers were willing to pay more for upgraded legroom, as the price was the first selection criteria for most aeroplane passengers [5]. Such premium economy concept was also seen as an additional revenue stream for long-haul LCCs since 4-6% of passengers were willing to upgrade their standard seat to a seat with extra space e.g. seats located at exit doors or bulkheads for €25-30 [1], which is a primary factor for passengers to opt for the premium economy [6]. Espino et al. [7] also found that passengers flying for 2.5-3 hours were even willing to pay €38 for this extra seat space. This willingness to upgrade to economy plus class increased for medium-haul flights and was even higher for long-haul flights [6]. Moreover, researchers also identified that the demands for the premium economy class had grown quickly, causing several airlines expanding the size of this cabin [8].

Anjani et al. [9] found that comfort increases when increasing seat pitch. This study was later compared to increased comfort when extending seat width by 1 inch [10]. Comparison of the results indicated that increasing the width by 1 inch increases comfort more than increasing the pitch by 2 inches, though both require the same additional space in the floor plan. And for reaching the same level of the comfort score of this additional 1 inch in width, 4-inch-increase in pitch direction is needed. Meanwhile, passengers were willing to pay an additional €22 for 1.5 extra inches of seat pitch and €29 for 3 to 6 extra inches of seat width from the basic 17-inch-wide 28-inch-pitch seat for a 4.5-5.5 hour flight, though these additions correlated negatively meaning that they were not willing to pay for both additions simultaneously [11]. Joen and Lee [12] also did a willingness-to-pay study for premium economy passengers travelling from Korea and found that passengers are willing to pay US$15.5, US$48.1 and US$114.0 for increased seat pitch or US$24.4, US$61.6 and US$144.4 for increased seat width for short-haul, medium-haul and long-haul flights, respectively. It is worth mentioning that passengers also said this might differ from really buying the extras.

Experts in the field usually will make the decision to choose between layouts. The knowledge and experience of these people is a worthwhile input for the management team's decision. Besides the scientific discoveries mentioned, experts who design the floor plan should also consider the complexity of the operations, the number of passengers on boards, the revenue of the airline, and aviation regulations (e.g. aisle width). All of these contribute to the complexity of designing the floor plan and selecting the types of seats for the premium economy class. On the other hand, advanced computational algorithms could optimize this layout which might be a better option. This leads to the research questions of this paper: 1) Which seat layout is more preferred by experts for the economy class in their view? 2) Which choice is more beneficial? And 3) How are the results of the seat layout by experts compared to the layout produced by the computational algorithms?

Literature Review

For airlines, it is important to differentiate from other airlines also within the cabin [13]. One way of differentiating is adding a premium economy or just a good economy class. In the assignment, the good economy class is described and, in this literature review, the focus is on premium economy class. Premium economy class was introduced to prevent business passengers from downgrading too much and giving an option to high-income leisure passengers to upgrade [8]. It provides a choice as an answer to most passenger dissatisfaction, which is seat comfort and legroom, luggage/flight disruptions and staff behaviours which occur in both LCCs and FSCs [14]. Moreover, Kim and Lee [15] found that intention to repurchase premium economy passengers will increase when they think premium economy service is well worth experiencing, where perceived service quality (e.g. in-flight service, wide and comfortable seats, and overall service quality) has the highest impact. The demand for the premium economy class in 2019 has increased from 2014 for all international markets, where an airline could charge at least 80% more of the cost of economy, and even four times higher for several routes [16]. Furthermore, domestic airlines in the United States of America are actively adding a premium economy class to their fleet after discovering its revenue-generating potential [17]

Adding a premium economy class itself adds complexity to the operation of the airliner. A differentiation needs to be made not only in the seats but also in other services provided by the airline [8, 18]. These pictures of a business class (Figure 1), premium economy (Figure 2) and economy class (Figure 3) seat are examples of the seat differentiation of each class for long-haul flights. Adding two types of economy class options will increase this complexity further as it needs two different types of seats. Even though Boeing introduced open architecture which gives flexibility in the interior with lots of seat combinations, it cost two years of planning before installing, and a considerable amount of man-hours were needed as well [19].

Figure 1. Example of a business class seat in a Boeing 777

Figure 2. Example of a premium economy class seat in a Boeing 787

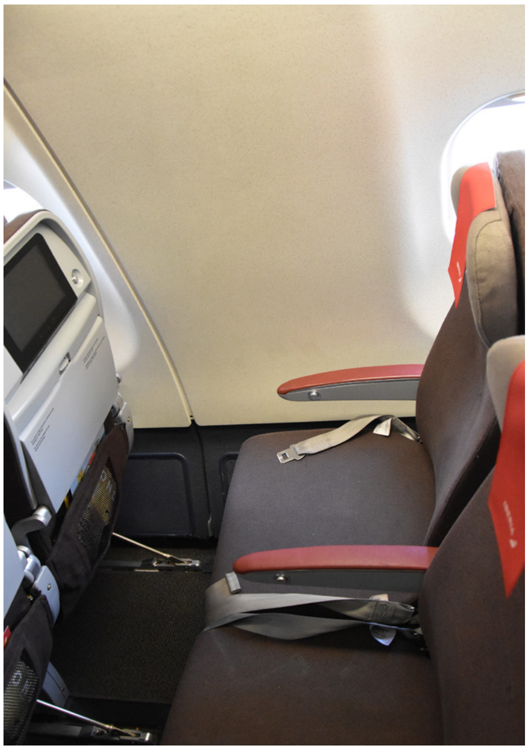

Figure 3. Example of an economy class seat in an Airbus A340

Kollmuss and Lane [20] found that in the US markets, the space for a first-class seat is 313% bigger than an economy seat, while a premium economy class seat only occupies 29% more space than an economy class seat. This extra space could be beneficial as ticket prices of premium economy seats are higher. However, it was also found that the production cost of the seat is also 1.6 times more expensive than economy class seats [8]. On the other hand, airlines also want to increase the number of seats in a cabin, as aeroplane manufactures predicted that adding another row in the aeroplane can reduce 5% of the seat cost per trip [21]. Seats in the aeroplane could be placed in different orientations. Amendment 25–20 of the Federal Aviation Administration (FAA), dated April 23, 1969, that seats with an angle of 0-18° to the centerline of the aeroplane both forward and backwards would have an adequate level of safety. Seats placed at an angle more than 18 degrees to the aeroplane centerline must be protected from head injury by airbags or a safety belt and an energy-absorbing rest that supports the arms, shoulders, head, and spine; or by a safety belt and shoulder harness that prevents the head from contacting injurious objects. FAA also regulates the size of the aisle to be a minimum of 15 inches for aeroplanes with more than 20 passengers. Another regulation Sec. 25.817 of the FAA states that there is a maximum of 3 seats beside each aisle per row which needs to also be considered. Additionally, some authors did research on the design of a premium economy class seat [22, 23], and others calculated the price dispersion changes when the premium economy class is introduced [24].

Materials and Methods

Eighty-eight experts in the field of aircraft interior were asked to make a floor plan of a part of a Boeing 777 aircraft of 5.87m wide and 3.7m long (Figure 4). Twenty-nine groups were made, and one person left during the workshop. Each group was given a printed scaled aircraft floor plan and two types of economy seats to choose from (Figure 5), and additional business class seats were given as a choice if they wanted more flexibility. Glue and scissors were provided to cut out the scaled seats and glue them on the floor plan. The sizes of the two types of economy seats were 17” x 34” and 18” x 30”, respectively, while the business class seats were 20” x 36”. These seats were also scaled on paper for the participants to cut and glue on the floor plan. During the session, experts could put contours of the top view of the seat (including legroom) on top of the given floor plan to make different arrangements using their experience and/or creativity. The end results of the workshop were photographed and analysed based on aviation regulations and the outcomes of previous studies. At the end of the session, a general evaluation was made, and experts were asked to give a reasoning for the decision. All floor plans were analyzed and compared based on their manufacturing complexity, the potential of the total ticket price, the perceptual choice, the number of seats installed and the width of the aisle.

A Python program was developed to use Skyline, Maximal Rectangles, and Guillotine algorithms [25] to find the optimal layouts in different configurations. In the setup of the configuration, three blocks of seats and two aisles were set up as the general layout and the following guidelines were given: 1) the widths of the blocks are adjustable; 2) the minimal aisle width was set following the regulations; 3) for each block, the type of seat is the same; and 4) the seats could be freely rotated. The objective functions of the optimization were set as either the floor plan with the most seats or with the highest added value. The optimization results were compared with the floor plans of the experts.

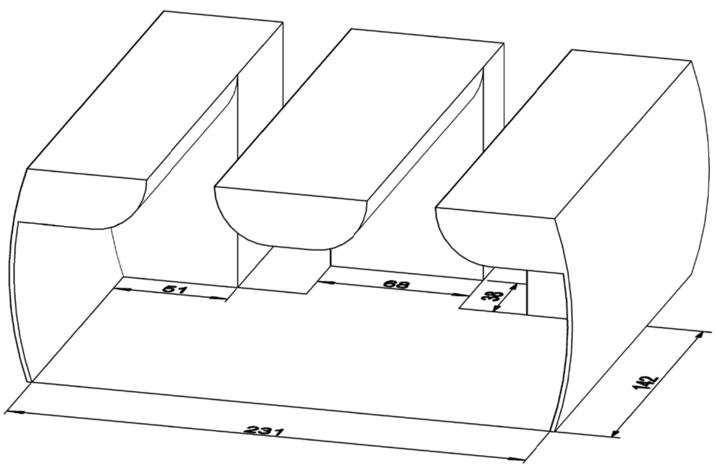

Figure 4. 3D drawing of cabin section between first class and economy class of Boeing 777 discussed in this study (unit: inch).

Results and Discussions

Twenty-nine floor-plans were collected from this workshop (Figure 6). Additionally, 126 floor-plans were generated by computational algorithms, where 64 allowed 90 degrees rotation and 62 were fixed facing forward. Fourteen groups of the workshop chose to only use the two types of economy class seats (floor plan no. 1-14). These photographed floor plans were analysed based on the complexity of the operations, the number of passengers on board, the revenue of the airline, and it might not follow some rules such as a minimum of 15 inches of aisle width. Since this aircraft has two aisles, the sufficient aisle width would be 30 inches.

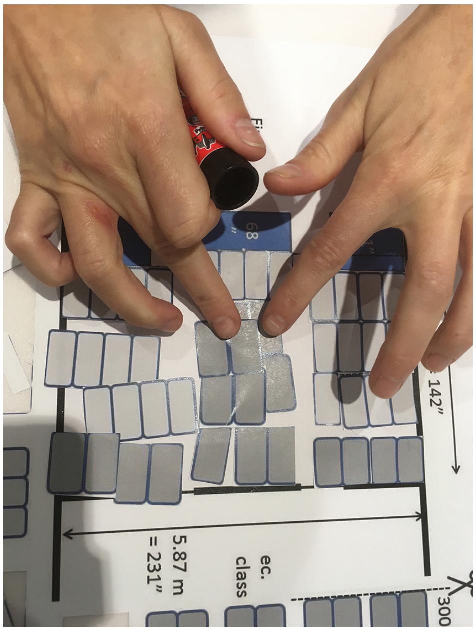

Figure 5. Discussion process of the workshop.

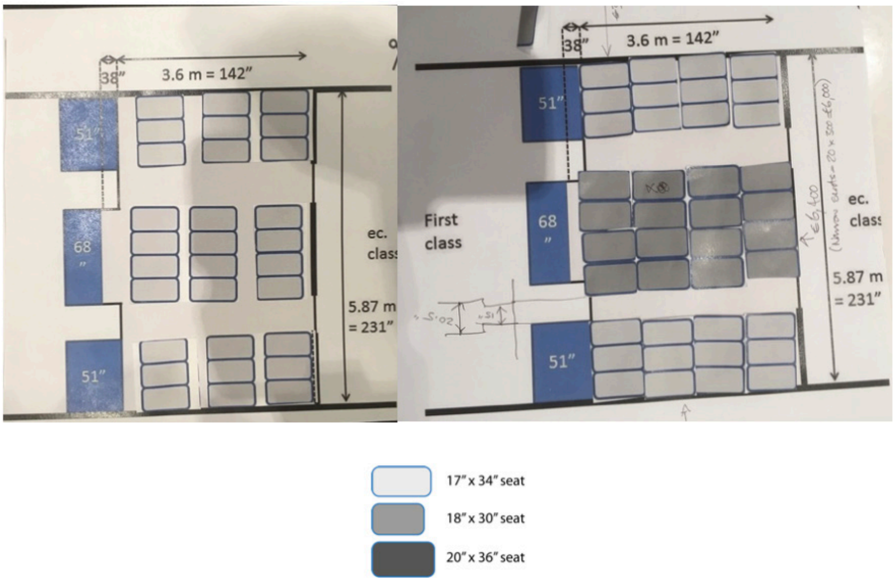

Figure 6. Examples of floor plans made by experts in the workshop of the study

Each group was provided with three different types of seats. Adding different seat types would increase the operational complexity as it would change the process of maintenance, booking, ticketing, etc. The number of seat types is included to give an overview of the complexity level of the operation.

The size choice of seats placed in the premium economy will affect the revenue of the airliner, as adding more seats can lead to a price reduction per seat, but having an upgraded space could attract the passengers to pay more [11, 21]. Calculations of the potential total of additional revenue were made based on the Willingness to Pay (WTP) prices of Balcombe et al. [11] when upgrading seat space from a basic 17-inch-wide 28-inch-pitch economy class seat for a 4.5-5.5 hours flight with LCCs. Each 17”x 34” seats were valued at €22 and the 18” x 30” seats were valued at €29 additionally. This upgrade could be attractive for economy and premium economy passengers since 68.1% perceived legroom as the source of discomfort, while 50.7% had high discomfort on seat width [26]. The complexity level, the aisle width, the additional value of floor plans and the numbers of seats were calculated as Table 1.

Table 1. Calculation of floor plans results made by experts in the workshop which only used premium economy class seats.

No.	18”x30”	17”x34”	Number of seat types	Aisle width (m)	Additional value	Seat Count
1	0	40	1	1.57	€880	40
2	0	30	1	1.57	€660	30
3	16	24*	2	1.53	€992	40
4	40	0	1	1.27	€1,160	40
5	38**	0	1	1.07	€1,102	38
6	16	24	2	1.45	€992	40
7	22**	24	2	1.45	€1,166	46
8	20	24	2	1.45	€1,108	44
9	0	44	1	1.14	€968	44
10	36	0	1	1.73	€1,044	36
11	20	24	2	1.45	€1,108	44
12	20	24	2	1.45	€1,108	44
13	20	24	2	1.45	€1,108	44
14	28	20	2	0.93	€1,252	48

*) Seats were placed sideways
**) Layout contained a second storey

In some plans, experts added an additional storey for more seats in the cabin. This did increase the numbers of seats, regulation-wise it might not be possible since each aisle only allows three seats on each side of the aisle. One group placed the 17” x 34” seat sideways for fitting more seats in. However, it is not yet known the comfort level of the passenger in this type of seat as the orientation of the seat might also influence the comfort level. No floor plans had an aisle width shorter than 0.76 m, though floor plan number 4 exceeded the given space. This floor plan with the highest additional revenue (€1,252) contains 28 seats of 18” x 30” and 20 seats of 17” 34” shown in Figure 7. This floor plan fits the regulations for 2 aisles, leaving a 0.93 m space, which will give each aisle width of 0.465 m = 18.3”.

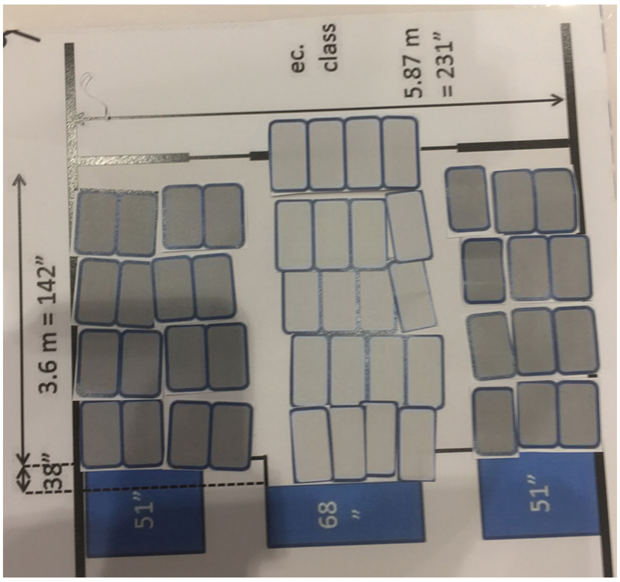

Figure 7. The floor plan made by experts that had the highest seat count of 48 seats and potential revenue of US$21,984.

Another comparison was made to see the maximum number of passenger on-board by combining business and premium economy class seats shown in Table 2. The floor plans that included the business class seats (floor plan no. 15-29) were included in this comparison. This calculation was based on a Boeing cost model for British Airways BA747- 400 aircraft from

London Heathrow to New York JFK in 2012 [8]. The real cost per passenger was US$ 766 for business class and US$ 359 for premium economy. While the real revenue per passenger was US$ 1,251 and US$ 817 for business and premium economy, respectively. The load factor for this route was included in the cost model. By comparing the potential profit from all floor plans, it was found that having a cabin with a premium economy class is more profitable than just having business class seats or even combining them. Among all floor plans that are complying with the regulations, the variation with 48 premium economy class without business class was found to gain more profit of US$ 21,984. This might be due to the different space-profit ratio of the business class and premium economy class seats. Therefore, adding the business class seat to this cabin section does not add to the profitability, though this calculation might change if the load factor of each class is added. The load factor used in the calculation of Hugon-Duprat and O'Connell [8] uses a 70%, 78% and 85% load factor for business, premium economy and economy, respectively. It is worth mentioning that the referenced profit/loss calculation had a longer seat pitch compared to the seats offered in this study.

Table 2. Profit/loss calculation for every floor plan made in the workshop by experts.

No.	Business class	Premium Economy	Comply **	Cost (US$)	Revenue (US$)	Profit/Loss (US$)
2	0	30	✓	10,770	24,510	13,740
25	21	13	×	20,753	36,892	16,139
16	7	28	✓	15,414	31,633	16,219
10	0	36	✓	12,924	29,412	16,488
24	19	16	×	20,298	36,841	16,543
18	12	24	✓	17,808	34,620	16,812
27	24	12	✓	22,692	39,828	17,136
5	0	39*	×	14,001	31,863	17,862
28	20*	18	×	21,782	39,726	17,944
17	9	30	✓	17,664	35,769	18,105
1	0	40	✓	14,360	32,680	18,320
3	0	40	✓	14,360	32,680	18,320
4	0	40	×	14,360	32,680	18,320
6	0	40	✓	14,360	32,680	18,320
22	16	24	✓	20,872	39,624	18,752
23	16	24	✓	20,872	39,624	18,752
26	24	16	✓	24,128	43,096	18,968
20	16	25	✓	21,231	40,441	19,210
21	16	25	×	21,231	40,441	19,210
15	6	36	✓	17,520	36,918	19,398
7	0	44*	×	15,796	35,948	20,152
8	0	44	✓	15,796	35,948	20,152
9	0	44	✓	15,796	35,948	20,152
11	0	44	✓	15,796	35,948	20,152
12	0	44	✓	15,796	35,948	20,152
13	0	44	✓	15,796	35,948	20,152
19	12	32	×	20,680	41,156	20,476
14	0	48	✓	17,232	39,216	21,984
29	52*	0	×	39,832	65,052	25,220

*) Layout contained a second storey
**) Regulations regarding the aisle width, given floor space and additional storey

Table 3. Optimal floor plans allowing rotation created by computer algorithm.

No.	Left		Middle		Right		Seat count	Profit/Loss (US$)
	Type	Count	Type	Count	Type	Count		
Rotate-1	17x34*	8	20x34	20	17x34*	8	36	17,028
Rotate-2	17x34*	8	17x34*	24	20x34	8	40	18,536
Rotate-3	17x34	12	17x34	20	20x34	8	40	18,536
Rotate-4	20x34	8	17x34*	24	17x34*	8	40	18,536
Rotate-5	20x34	12	17x34*	16	17x34	12	40	18,644
Rotate-6	17x34	12	17x34*	16	20x34	12	40	18,644
Rotate-7	20x34	12	17x34*	16	17x34	12	40	18,644
Rotate-8	17x34	12	20x34	16	17x34	12	40	18,752
Rotate-9	20x34	8	17x34*	24	20x34	8	40	18,752
Rotate-10	20x34	8	18x30*	24	20x34	8	40	18,752
Rotate-11	17x34	12	20x34	16	17x34	12	40	18,752
Rotate-12	20x34	12	17x34*	16	20x34	12	40	18,968
Rotate-13	20x34	12	18x30*	16	20x34	12	40	18,968
Rotate-14	20x34	12	17x34*	16	20x34	12	40	18,968
Rotate-15	20x34	12	18x30*	16	20x34	12	40	18,968
Rotate-16	17x34	12	20x34	16	20x34	12	40	19,076
Rotate-17	20x34	12	20x34	16	17x34	12	40	19,076
Rotate-18	17x34	12	20x34	16	20x34	12	40	19,076
Rotate-19	20x34	12	20x34	16	17x34	12	40	19,076
Rotate-20	20x34	12	20x34	16	20x34	12	40	19,400
Rotate-21	20x34	12	20x34	16	20x34	12	40	19,400
Rotate-22	17x34	12	17x34	20	17x34	12	44	20,152
Rotate-23	17x34	12	17x34	20	18x30	12	44	20,152
Rotate-24	18x30	12	17x34	20	17x34	12	44	20,152
Rotate-25	18x30*	16	17x34*	16	17x34	12	44	20,152
Rotate-26	17x34	12	17x34	20	17x34	12	44	20,152
Rotate-27	17x34	12	17x34*	16	18x30*	16	44	20,152
Rotate-28	18x30*	16	17x34*	16	17x34	12	44	20,152
Rotate-29	17x34	12	18x30*	24	20x34	8	44	20,368
Rotate-30	18x30	12	18x30*	24	20x34	8	44	20,368
Rotate-31	20x34	8	18x30*	24	17x34	12	44	20,368
Rotate-32	20x34	8	18x30*	24	18x30	12	44	20,368
Rotate-33	17x34	12	18x30*	24	20x34	8	44	20,368
Rotate-34	20x34	8	18x30*	24	17x34	12	44	20,368
Rotate-35	18x30*	16	17x34*	16	20x34	12	44	20,476
Rotate-36	18x30*	16	18x30*	16	20x34	12	44	20,476
Rotate-37	20x34	12	17x34*	16	18x30*	16	44	20,476
Rotate-38	20x34	12	18x30*	16	18x30*	16	44	20,476
Rotate-39	18x30*	16	17x34*	16	20x34	12	44	20,476
Rotate-40	18x30*	16	18x30*	16	20x34	12	44	20,476
Rotate-41	20x34	12	17x34*	16	18x30*	16	44	20,476
Rotate-42	20x34	12	18x30*	16	18x30*	16	44	20,476

Table 3. Optimal floor plans allowing rotation created by computer algorithm (cont'd)

No.	Left		Middle		Right		Seat count	Profit/Loss (US$)
	Type	Count	Type	Count	Type	Count		
Rotate-43	17x34	12	20x34	16	18x30*	16	44	20,584
Rotate-44	18x30*	16	20x34	16	17x34	12	44	20,584
Rotate-45	17x34	12	20x34	16	18x30*	16	44	20,584
Rotate-46	18x30*	16	20x34	16	17x34	12	44	20,584
Rotate-47	20x34	12	20x34	16	18x30*	16	44	20,638
Rotate-48	18x30*	16	20x34	16	20x34	12	44	20,908
Rotate-49	20x34	12	20x34	16	18x30*	16	44	20,908
Rotate-50	18x30*	16	20x34	16	20x34	12	44	20,908
Rotate-51	17x34	12	18x30*	24	17x34	12	48	21,984
Rotate-52	17x34	12	18x30*	24	18x30	12	48	21,984
Rotate-53	18x30*	16	17x34*	16	18x30*	16	48	21,984
Rotate-54	18x30	12	18x30*	24	17x34	12	48	21,984
Rotate-55	18x30	12	18x30*	24	18x30	12	48	21,984
Rotate-56	18x30*	16	18x30*	16	18x30*	16	48	21,984
Rotate-57	17x34	12	18x30*	24	17x34	12	48	21,984
Rotate-58	17x34	12	18x30*	24	18x30	12	48	21,984
Rotate-59	18x30*	16	17x34*	16	18x30*	16	48	21,984
Rotate-60	18x30	12	18x30*	24	17x34	12	48	21,984
Rotate-61	18x30	12	18x30*	24	18x30	12	48	21,984
Rotate-62	18x30*	16	18x30*	16	18x30*	16	48	21,984
Rotate-63	18x30*	16	20x34	16	18x30*	16	48	22,416
Rotate-64	18x30*	16	20x34	16	18x30*	16	48	22,416

*) Seat rotated 90 degrees

In some layouts, some seats were rotated 90 degrees for maximizing the capacity towards the objective functions. However, whether this configuration is comfortable for passengers is still unknown. Adding seats will increase the additional revenue, though ingress and egress might cause a problem. This rotated position could also introduce extra manufacturing costs, as usually seats are manufactured in groups of 3 or 4 in a row. In order to place the seats sideways, additional airbags should be installed in the seatbelt and/or in the walls. The dimension of the additional equipment is not calculated in the layouts, as well as the additional manufacturing cost of the seat.

The highest seat count for the computer allowing rotation was 48 seats with only premium economy class seats. The for layouts that included business class seats, the layout with the maximum seat count could board 16 business class passengers and 32 premium economy class passengers on-board (Figure 8).

Another calculation was done for seat layouts with all passengers facing flight direction. Sixty-two layouts were generated from this algorithm (Table 4). With this facing forward restriction, the seat count decreased to 44. There were 16 layouts with the same seat count. These layouts consisted of either or a mix of 18″ x 30″ and 17″ x 34″ seats, examples shown in Figure 9, though having chosen the wider option could attract passengers to pay more.

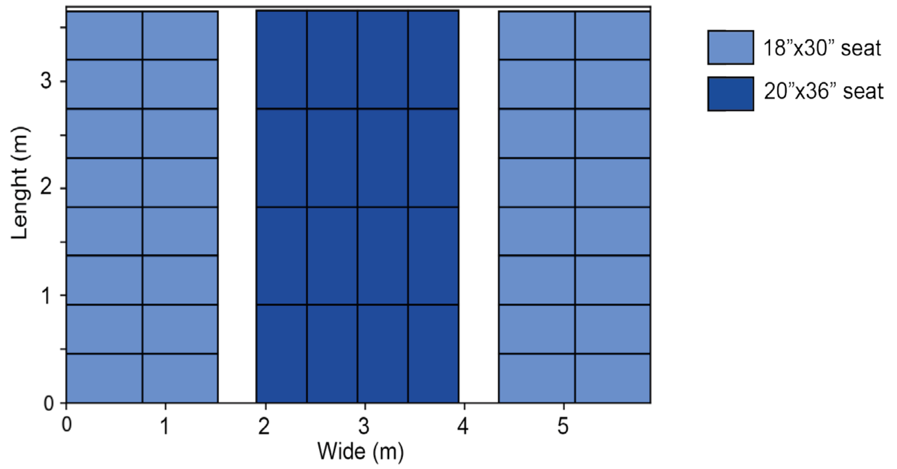

Figure 8. Floor plan allowing seat rotation with the highest seat count of 48 seats and highest potential revenue of US$22,416 generated with by the computer algorithm

Table 4. Optimal floor plans with all seats facing forward created by computer algorithm.

No.	Left		Middle		Right		Seat count	Profit/Loss (US$)
	Type	Count	Type	Count	Type	Count		
Forward-1	17x34	8	20x36	20	17x34	8	36	17,028
Forward-2	17x34	8	17x34	24	20x36	8	40	18,536
Forward-3	17x34	12	17x34	20	20x36	8	40	18,536
Forward-4	17x34	12	18x30	20	20x36	8	40	18,536
Forward-5	18x30	8	17x34	24	20x36	8	40	18,536
Forward-6	18x30	12	17x34	20	20x36	8	40	18,536
Forward-7	18x30	12	18x30	20	20x36	8	40	18,536
Forward-8	20x36	8	17x34	24	17x34	8	40	18,536
Forward-9	20x36	8	17x34	24	18x30	8	40	18,536
Forward-10	20x36	8	18x30	20	17x34	12	40	18,536
Forward-11	20x36	8	18x30	20	18x30	12	40	18,536
Forward-12	20x36	12	17x34	16	17x34	12	40	18,644
Forward-13	20x36	12	17x34	16	18x30	12	40	18,644
Forward-14	20x36	12	18x30	16	17x34	12	40	18,644
Forward-15	20x36	12	18x30	16	18x30	12	40	18,644
Forward-16	17x34	12	17x34	16	20x36	12	40	18,644
Forward-17	17x34	12	18x30	16	20x36	12	40	18,644
Forward-18	18x30	12	17x34	16	20x36	12	40	18,644
Forward-19	18x30	12	18x30	16	20x36	12	40	18,644
Forward-20	20x36	12	17x34	16	17x34	12	40	18,644
Forward-21	20x36	12	17x34	16	18x30	12	40	18,644
Forward-22	20x36	12	18x30	16	17x34	12	40	18,644
Forward-23	20x36	12	18x30	16	18x30	12	40	18,644
Forward-24	17x34	12	20x36	16	17x34	12	40	18,752
Forward-25	17x34	12	20x36	16	18x30	12	40	18,752
Forward-26	18x30	12	20x36	16	17x34	12	40	18,752
Forward-27	18x30	12	20x36	16	18x30	12	40	18,752
Forward-28	20x36	8	17x34	24	20x36	8	40	18,752
Forward-29	17x34	12	20x36	16	17x34	12	40	18,752

Table 4. Optimal floor plans with all seats facing forward created by computer algorithm (con'd).

No.	Left		Middle		Right		Seat count	Profit/Loss (US$)
	Type	Count	Type	Count	Type	Count		
Forward-30	17x34	12	20x36	16	18x30	12	40	18,752
Forward-31	18x30	12	20x36	16	17x34	12	40	18,752
Forward-32	18x30	12	20x36	16	18x30	12	40	18,752
Forward-33	20x36	12	17x34	16	20x36	12	40	18,968
Forward-34	20x36	12	18x30	16	20x36	12	40	18,968
Forward-35	20x36	12	17x34	16	20x36	12	40	18,968
Forward-36	20x36	12	18x30	16	20x36	12	40	18,968
Forward-37	17x34	12	20x36	16	20x36	12	40	19,076
Forward-38	18x30	12	20x36	16	20x36	12	40	19,076
Forward-39	20x36	12	20x36	16	17x34	12	40	19,076
Forward-40	20x36	12	20x36	16	18x30	12	40	19,076
Forward-41	17x34	12	20x36	16	20x36	12	40	19,076
Forward-42	18x30	12	20x36	16	20x36	12	40	19,076
Forward-43	20x36	12	20x36	16	17x34	12	40	19,076
Forward-44	20x36	12	20x36	16	18x30	12	40	19,076
Forward-45	20x36	12	20x36	16	20x36	12	40	19,400
Forward-46	20x36	12	20x36	16	20x36	12	40	19,400
Forward-47	17x34	12	17x34	20	17x34	12	44	20,152
Forward-48	17x34	12	17x34	20	18x30	12	44	20,152
Forward-49	17x34	12	18x30	20	17x34	12	44	20,152
Forward-50	17x34	12	18x30	20	18x30	12	44	20,152
Forward-51	18x30	12	17x34	20	17x34	12	44	20,152
Forward-52	18x30	12	17x34	20	18x30	12	44	20,152
Forward-53	18x30	12	18x30	20	17x34	12	44	20,152
Forward-54	18x30	12	18x30	20	18x30	12	44	20,152
Forward-55	17x34	12	17x34	20	17x34	12	44	20,152
Forward-56	17x34	12	17x34	20	18x30	12	44	20,152
Forward-57	17x34	12	18x30	20	17x34	12	44	20,152
Forward-58	17x34	12	18x30	20	18x30	12	44	20,152
Forward-59	18x30	12	17x34	20	17x34	12	44	20,152
Forward-60	18x30	12	17x34	20	18x30	12	44	20,152
Forward-61	18x30	12	18x30	20	17x34	12	44	20,152
Forward-62	18x30	12	18x30	20	18x30	12	44	20,152

Overall, both experts and computer program showed that the maximum seat count is 48, although experts used a mixture of only premium economy seats facing forward, while the computer program mixed premium economy and business class seats with rotated-seats. Experts paid more attention to the comfort perceived by passengers using the information briefed before the group discussion, though the computer program was better at getting a floor plan that gives higher potential revenue. Computer programs also have a strict rule of constraints, so the layouts made would follow all regulations, yet the experts are more creative in making ideas for future floor plans.

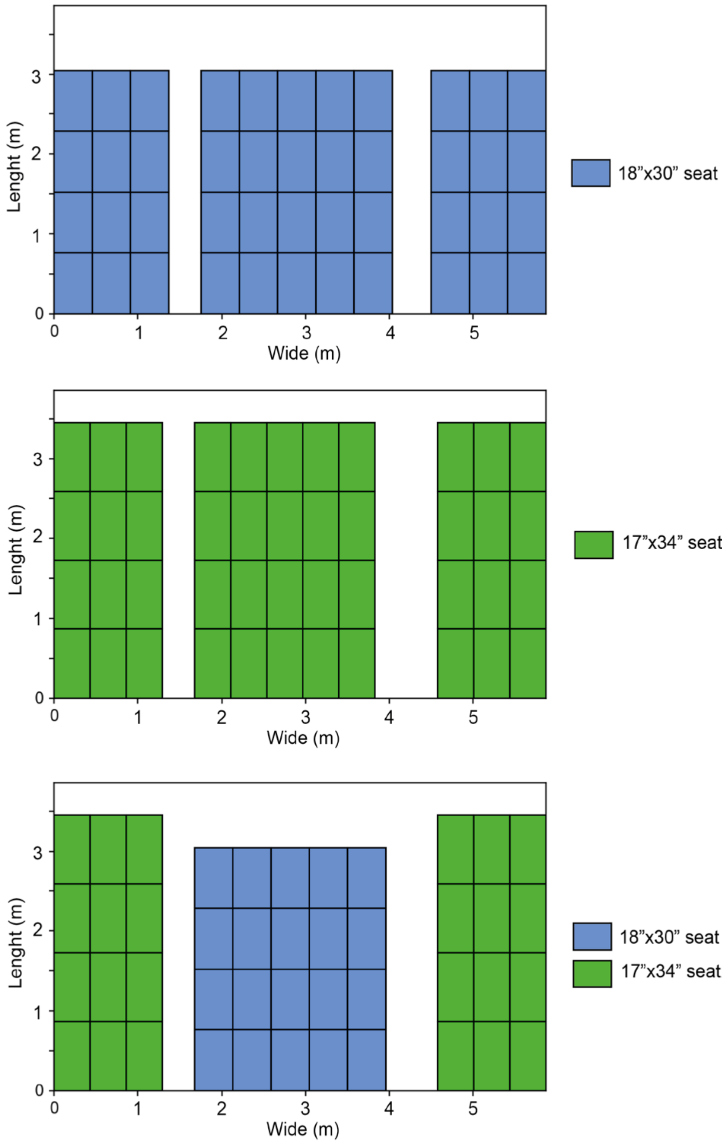

Figure 9. Examples of optimal layout facing forward with the highest seat count of 44 seats and highest potential revenue of US$ 20,152 generated by the computer algorithm

There are several limitations to this study. Each airline has a different label for their premium economy class, where the seat space dimensions also differ among airlines. Experts that participated in the workshop did affirm the chosen seat sizes in this experiment. This study also did not clearly define the duration of the flight for the section of cabin designed. There is a chance that the size of seats needs to be larger for long-haul flights. Moreover, there is a limited number of available references on premium economy class, especially with the same dimensions used during this study, limiting the discussion of this paper.

Conclusion and Future Work

This study tries to explore the potential of the floor plans of the economy cabin using two types of economy class seats. Aircraft interior experts were asked to make floor plans with comfort as a consideration, which were analysed based on the complexity of the operations, the number of passengers on boards, the revenue of the airline, and its aisle width. Fourteen groups of experts used only the economy class seats. These floor plans were then photographed, and the potential additional revenues were calculated. The most profitable plan using premium economy class seats was using 28 seats of 18″x30″ and 20 seats of 17″x34″ resulting in US$21,984 of potential revenue with the highest seat count of 48 seats. Adding the business class seats to the floor plan did not increase the potential profit of the cabin section.

The results of the experts are then compared to the 126 layouts generated by computational algorithms. In these layouts, a rotation was allowed without considering comfort. The results show having a section with business class seats turned out to have a higher potential revenue of US$22,416. This combination has 32 seats of 18”x30” rotated and 16 seats of 20”x36”. The highest seat count was 48, the same as the results from experts.

Overall, experts were better at using comfort knowledge and are more out-of-the-box in making future floor plans though some ideas did not follow the regulations. The results of the computer program had higher potential revenue by adding business class seats. The use of the computer resulted in optimal use of the space and would ensure all regulations are met, though some floor plans contained rotated seats where the comfort is still unknown.

This study explores this seat configuration modelling by aircraft interior experts, where comfort was one of the main goals. Besides the listed criteria, other researchers also investigated aircraft seating layout by measuring load/unload time of passengers [27–30]. Another study also tries to model an aircraft seat configuration by maximizing customer satisfaction and in-flight safety as well as being profitable for the airliners [31]. They utilized tools such as digital human models, layout optimization, and a profit-maximizing constraint to their model for an optimal floor plan. Further studies are needed to understand the impact of having different types of seats in one cabin, the effect on seat rotation, its effect on the loading and unloading process and optimizing the floor plan based on those understands.

There are several limitations to this study. Each airline has a different label for their premium economy class, where the seat space dimensions also differ among airlines. This study also did not clearly define the duration of the flight for the section of cabin designed. Moreover, there is a limited number of available references on premium economy class, especially with the same dimensions used during this study, limiting the discussion of this paper.

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CHAPTER 6

Discussion and Conclusion

General Discussion

Most passengers select their flight by finding the most convenient route and departure time at the best price, and when the choice is similar, aspects such as comfort, service, airline reputation and marketing programs are considered [1]. To offer the best price, airlines need to board as many passengers as possible, Therefore, space is valuable, and the passengers' individual space is then limited. Even though less common, some passengers would choose a slightly less convenient flight or a slightly higher fare to fly aboard their favourite airline, where the reason is the value of comfort [1]. These facts show that having comfort at the best price in an airplane interior adds a competitive advantage to the airlines, where limited space is a constraint. However, there is not much information on how comfort-experience is influenced by small changes in the aircraft interior.

The research objective of this thesis was to increase aircraft passengers' comfort by creating knowledge on those physical entities that predict comfort. Additionally, there was a gap in knowledge understanding the elements in the process from physical entities (PE) to experiencing comfort (C). This chapter provides an overview of the results from each chapter and recommendations for future research.

Overview of the Results

In **Chapter 1** an overview of the intended research of this PhD thesis is described. The assumed comfort definition and applied models are provided, and the structure and context of the research is detailed. This PhD is structured following the model of Vink and Hallbeck [2] in which the physical entities (PE) result in an interaction (I) between human and physical entities, which results in a physical effect in the human body (H), which is perceived (P) and therefore determine whether comfort or discomfort is experienced (C) as is shown in Figure 1.

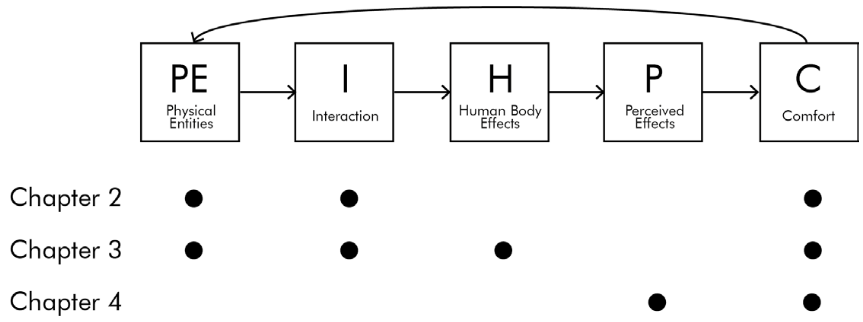

Figure 1. The main point of attention in Chapter 2, 3, and 4 linked to the model in which steps between physical entities and comfort are described.

Chapter 2 presents an interaction (I) between the human and aircraft seats leading to a certain level of comfort. The studies of this chapter are within-subject studies conducted in a Boeing 737 fuselage. The dimensions of the seat space were varied to test the effects of this change in interaction. The first study evaluated the relationship between human anthropometrics and the space experience by passengers in different pitch lengths (PE). This study shows that passengers with a higher popliteal height, a longer buttock-knee depth, a higher eye height sitting and a higher sitting height show more discomfort with a reduced pitch then shorter passengers. It also shows that pitch lengths of 28" correspond to comfort scores of around 4 on a 10-point scale, which Is very low. Another analysis demonstrated a significant relationship between seat pitch and comfort as well as discomfort (C). Additionally, it was found that the mean score of discomfort for the middle seat was higher than the window and aisle seat.

In the second study, the seat width was varied and effects on comfort and discomfort were recorded. This addition in seat width reduced discomfort on the shoulders, knees, and lower legs and feet. Also, relationships with anthropometrics were studied. The participants with a smaller hip-breadth felt more comfort while sitting in the 18-inch-wide seat, which results in more movement space for the human body which is relevant as a variation of posture is important to prevent discomfort. This shows that interaction (I) between the human physical entities and environmental physical entities (PE) influences comfort (C). The study also showed that to reach a similar level of comfort, increasing the width of a 17-inch-wide seat by 1 inch might be more efficient than increasing the pitch by 4 inches, which is an important finding in considering the usage of floor areas.

Human body effects (H) were the focus of **Chapter 3**. Heart rate variability (HRV) was measured for passengers during 2-hours of sitting in an airplane seat. A simulation of take-off and landing with seat belts fastened for 5 minutes each were added in the beginning and end. Participants used half the time to work using the tray table, and the other half with the tray table folded. A snack and drink were provided in the middle of the experiment to simulate the flight experience. Interactions (I) between the human and aircraft seats were used as the basis for the experimental design. Four seats with two different pitches (28-inch and 30-inch) and widths (17-inch and 18-inch) were compared within-subjects in this study. Interestingly, the seat with the least space did not perform the worst in this study, which might be caused by the use of the tray table in the first half of the experiment. This study found that most HRV parameters were related to comfort, but not so much to discomfort (C), probably because the heart rate is more related to emotions than to the lack of physical space. This could indicate that HRV could be used as a human-body effect indicator in predicting comfort as comfort was found to be related to more HRV parameters that are correlated to well-being, emotions and psychological states. Additionally, subjective discomfort was found to increase over time and corresponded to some parameters of the HRV. Over all parameters, the HRV parameters SDNN, HF and SD2 seem promising especially when recording changes over time. It has the strongest relationship with comfort and it is fairly easy to record.

In **Chapter 4**, the perceived effects (PE) and comfort (C) are the main topic. There are many questionnaires on comfort available for use. However, it is the question of which questionnaire is most applicable for which situation. An overview of subjective assessment methods of comfort is presented in the list of Preferred Comfort Questionnaires (PCQ) of product design. Fifteen candidate questionnaires on comfort were selected and ranked by 55 comfort researchers and practitioners in a workshop. The criteria of rating and ranking included easiness to answer, easiness for data interpretation, the time needed to complete, the need for prior training, as well as mapping the applicable design phases and field of application. A PCQ for comfort research was generated for five proposed application fields and four design phases, the preferred questionnaires were highlighted and categorized into four categories: preferred questionnaire, suitable for less prior training, suitable for fast completion and generally applicable, which led to a list of PCQ for Product Design. This PCQ list can be used as an instrument to help researchers in selecting questionnaires for comfort research in product design.

An application of background knowledge influencing comfort and discomfort is presented in **Chapter 5**. Aircraft interior experts were given the possibility to use the knowledge generated in previous chapters. These experts were asked to make floor plans with comfort as a consideration. The results were then analysed based on the complexity of the operations, the number of passengers on boards, the revenue of the airline, and its aisle width. The most profitable plan made by experts using premium economy class seats consisting of 28 seats of 18”x30” and 20 seats of 17”x34” resulting in US$21,984 of potential revenue due to the highest seat count of 48 seats. Adding the business class seats to the floor plan did not increase the potential profit of the cabin section. The results of the experts are then compared to the layouts generated by computational algorithms where rotations are allowed without considering comfort. The results show having a section with business class seats turned out to have a higher potential revenue of US$22,416. It consisted of a combination of 32 seats of 18”x30” rotated and 16 seats of 20”x36”. The highest seat count was 48, the same as the results from experts. Overall, experts were better at using comfort knowledge and are more out-of-the-box in making future floor plans though some ideas did not follow the regulations, e.g. making a second storey seat. The results of the computer program had higher potential revenue by adding business class seats. The use of the computer resulted in optimal use of the space and would ensure all regulations are met, though some floor plans contained rotated seats where the comfort is still unknown.

Oborne [3] stated that comfort is a subjective phenomenon and it is difficult to define and measure. Models are made to have a better grasp of the subjective feeling of the passenger. This thesis uses the comfort model of Vink and Hallbeck [2] and an attempt has been made to detail the model and quantifies relationships within the model. The result of this PhD is a map on the relationship between physical entities of the environment and comfort shown in Figure 2.

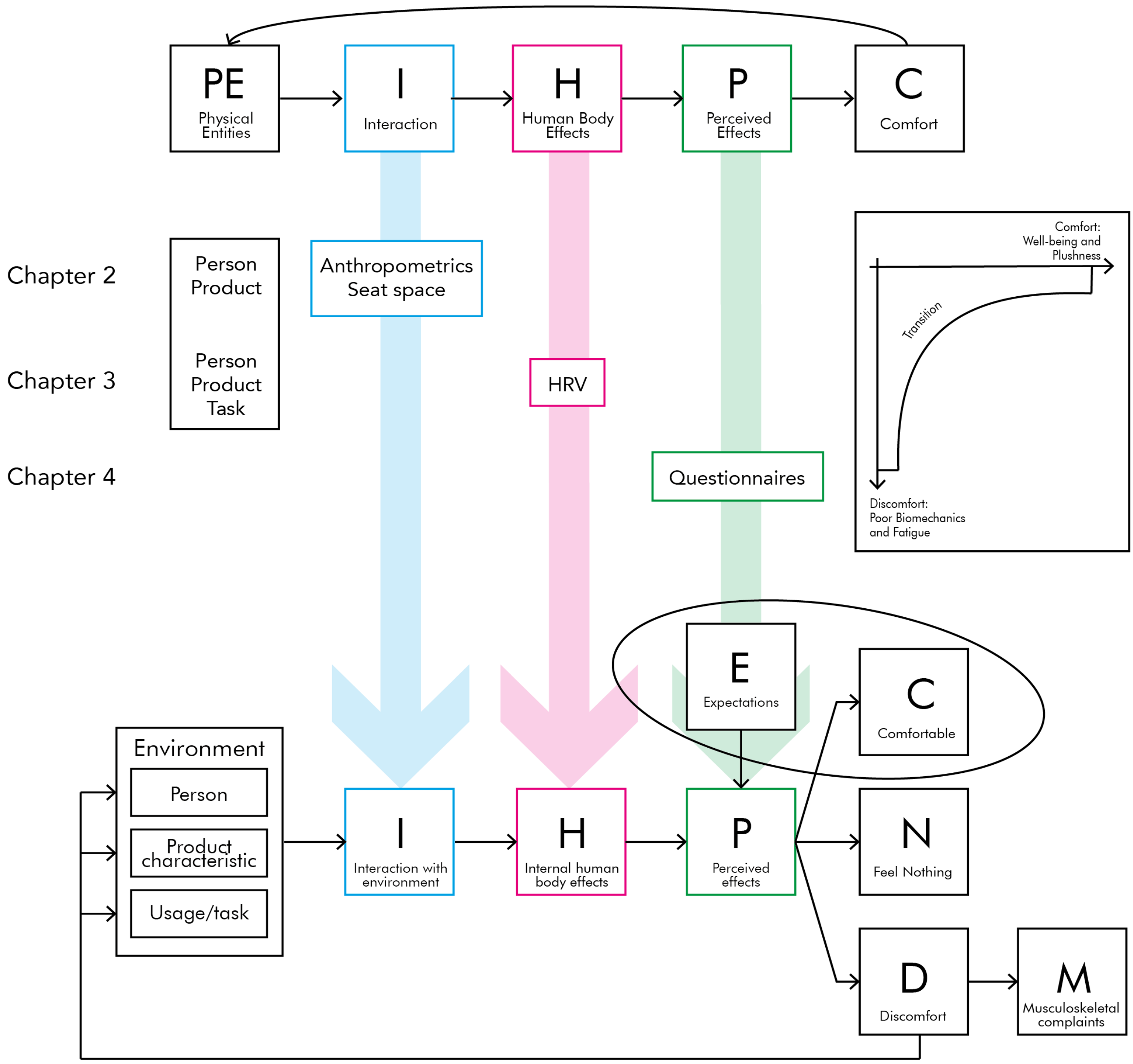

Figure 2. Summary of the research: Knowing I, H and/or P comfort can be predicted.

Experiments with a variety of participants, products, and tasks were conducted and measurements of the interaction, human body effects and perceived effects were taken. These studies prove that indeed comfort and discomfort are a clear result of the interaction, the human body effects and the perceived effects, and quantifying helped in predicting comfort. Comfort can be predicted, for instance, based on pitch and width knowing the anthropometrics of the occupants (see Chapter 2), and based on HRV parameters (see Chapter 3) but this needs further exploration.

Reflection

The research objective of this thesis was narrowed down into three phases and six research questions. As a reflection, we listed our answers to these six research questions are:

Phase 1 - RQ 1: What is the relationship between seat pitch and comfort, and what are the roles of different factors in this process, such as space experience and anthropometrics?

A significant relationship between seat pitch and comfort as well as the discomfort has been found. A lower pitch reduces comfort and increases discomfort significantly. The anthropometric measurements of the larger sized participants significantly affect the (dis)comfort on smaller pitch sizes. All comfort and discomfort statements on space experience were also found to have a correlation to the pitch sizes.

Phase 1 - RQ2: What is the relationship between space experience and human anthropometrics at different seat pitches?

Passengers with a higher popliteal height and a longer buttock-knee depth show more negative results in space experience with reduced pitch compared to shorter passengers. Therefore, the taller the passenger is, the larger the problems could be expected with low seat pitches, physiological as well as psychological.

Phase 1 - RQ3: What is the effect of widening a seat from 17" to 18" on comfort? And is the effect of widening the seat comparable to the increase of a certain pitch?

Participants felt more comfort and less discomfort when sitting in the 18-inch-wide seats compared with sitting in the 17-inch-wide seats. This width-increase also reduced the discomfort of all body parts except the buttocks. It was also found that the level of comfort of increasing an inch of the width of a 17-inch-wide seat is comparable to increasing the pitch by 4 inches.

Phase 2 - RQ4: Does comfort and discomfort change over time regarding different types of seats? Are there any relationships between various metrics of HRV and the feeling of comfort/discomfort of passengers? And if so, which parameters of HRV can be used in predicting comfort/discomfort over time?

The discomfort did increase over time, while comfort decreased. The results indicate that almost all parameters of HRV, except Mean NN and Mean HR, were significantly correlated to the comfort ratings gathered with the questionnaires. The discomfort had the highest correlation with the LF norm and HF norm even though the correlations were not strong. For future research, SDNN, HF and SD2 might be interesting parameters to apply, because they have the best correlation to subjective comfort and discomfort and could indicate the changes over time.

Phase 3 - RQ5: Which questionnaires can be included in the Preferred Comfort Questionnaires (PCQ) list for product design?

The research showed that selecting the best comfort or discomfort questionnaires is possible, but it is strongly dependent on the type of research and the phase in the design process of which questionnaire is preferred. A list of PCQ for Product Design was proposed regarding different design phases and application fields, and we expected this list can be used as an instrument to help researchers in selecting questionnaires in comfort research.

Overall- RQ6: Which seat configuration is more preferred by experts for the premium economy? And which choice is more beneficial?

Fourteen out of twenty-nine groups of experts chose to only use premium economy seats in the floor plan, where a combination of 48 premium economy seats resulted in the highest estimated profit. This result was compared to the results of a computer program which found that the highest expected profit was acquired using a floor plan that allows a rotation of 90 degrees for the seats and included business class chairs.

Meta-analysis on the (dis)comfort studies

Comfort and Discomfort Relationship

Zhang et al. [4] made a model on the relationship between comfort and discomfort. In this PhD this relationship is further quantified. Zhang et al. [4] showed a transition of comfort and discomfort in two different axes. This study used both comfort and discomfort recordings and it was found that this relationship also does exist based on more quantitative data as shown in Figure 3.

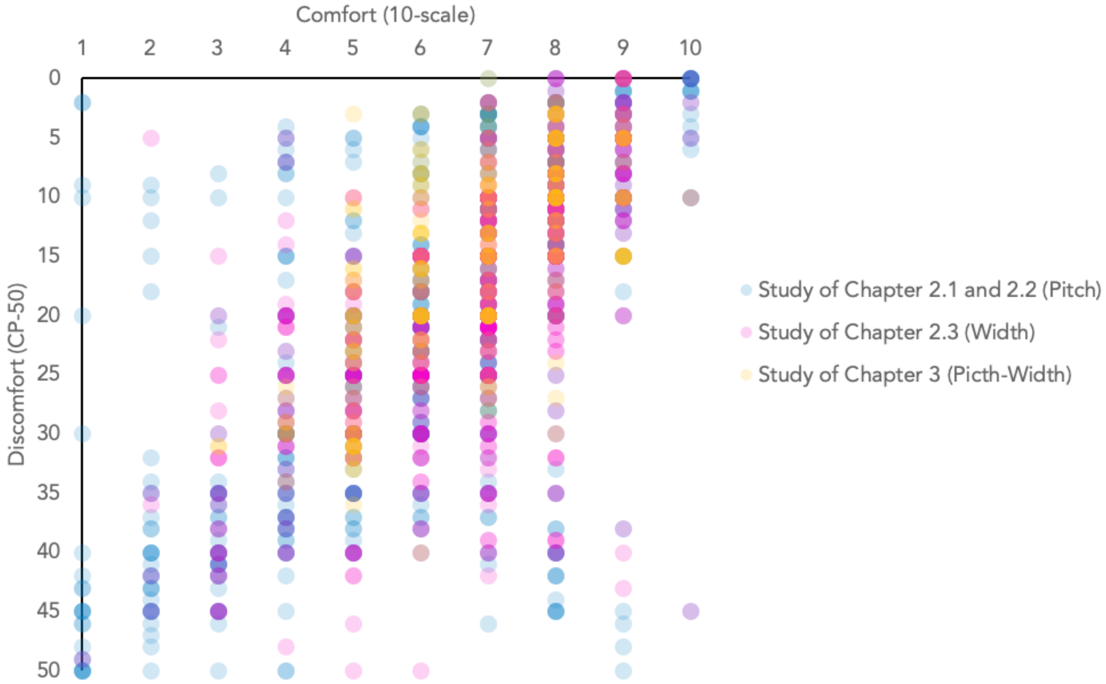

Figure 3. The relationship between comfort (x-axis) and discomfort (y-axis) if the outcomes of all experiments in this PhD are plotted in one graph, the yield curve described by Zhang et al. [4] can be found in this PhD as well although it Is closer to linear than described by Zhang et al. [4].

A meta-analysis is done on the relationship between comfort and discomfort based on the results of all subjective questionnaires of the 3 studies (see Figure 3). The blue dots are data from Chapter 2.1 and 2.2, the pink dots are data from Chapter 2.3 and the yellow dots are data from Chapter 3. This analysis shows that comfort and discomfort could occur at the same time based on the theory of Zhang et al. [4] and Helander and Zhang [5].

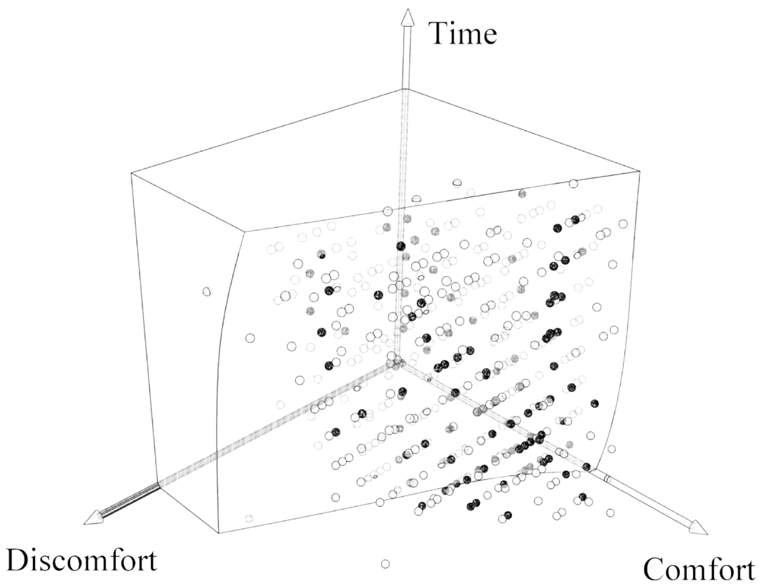

Figure 4. Changes of comfort and discomfort overtime

Comfort Over Time

In the research of Vink et al. [6], comfort and discomfort are found to be influenced by previous experiences and changes over time. The response of a passenger would depend on the length of the journey, as for long travels fatigue and discomfort are expected to rise [3]. Therefore, the time factor was studied and results showed a change in comfort and discomfort over a span of 2 hours. Other studies also detected a change of comfort and discomfort over time by observing small movement and fidgets [7] and HRV [8]. The main effect Is that comfort reduces over time If there are no breaks and discomfort Increases.

Our studies affirmed that the interaction between comfort and discomfort is still present as in the theory of Zhang et al. [4]. Since there is a change over time in this comfort and discomfort rating, the third axis of time could be added to this interaction. Figure 4 presents a graph with this change over time.

This meta-analysis from the questionnaire data of Chapter 3 is shown over time (see Figure 4). The discomfort line in this analysis does increase over time, and studies by Smulders et al. [9] and Li et al. [10] showed likewise.

Recording discomfort and comfort

This study shows that comfort is linked to discomfort on a different axis, while other studies (e.g. Looze et al. [7]). strengthen the relationship between discomfort and pressure distribution. The study of Kruithof et al. [8] showed that pressure distribution is connected to posture, and heart rate to excitement playing a game. So, more studies indicate that comfort can be recorded by heart rate and discomfort to pressure distribution, which is the advice based on this PhD.

Future Work

There many of definitions perceived comfort. 579 articles were found when perceived comfort is searched on Scopus with a large variety of participants, tasks, objects and measurement methods used. Often questionnaires are used to study comfort or discomfort. The most important versions or questionnaires are included in the PCQ chapter. A questionnaires is a method to evaluate experienced comfort. The advancement of technology enables researchers to gather more data on factors influencing comfort without interfering with the participant. This can contribute to a solution to overcome the difficultly of continuously asking participants to self-assess their comfort for measuring current comfort status. Comfort is a psychological effect that sometimes is not noticeable. If people are asked about their current comfort level, they will be more aware, and this itself might influence the judgments. Asking questions in the middle of a task might also disturb the actual condition in reality, while the aim of a comfort designer should be to not intrude on the passengers' awareness [3]. The use of cameras for observing participants can overcome this problem partly. Studies have shown that observing small movements and fidgets (SMFs) can detect the discomfort level of a driver [7, 13]. The number of SMFs per 10 minutes is found to be a good indicator of a person's seat discomfort rating [14]. The way people sit and communicate could also be observed via the camera [15, 16]. Video recording is also a good way to report comfort for people who have difficulties in filling questionnaires for example children [17, 18] and automatic analysing the videos with artificial intelligence is getting easier as well [19].

Moreover, cameras can also record facial expressions and categorize these in emotions, which might also indicate the level of comfort. This facial expression method has been used to detect thermal comfort [20], the comfort of video calling [21] and visual discomfort [22]. One study also used this technology to evaluate passenger seat comfort in airplanes [23]. Future studies could also use non-interfering methods like this to evaluate passenger comfort, which gives the possibility to do a long-term observation in a real-life setting.

Also, the HRV parameters studied in this PhD are promising and could be further explored.

There are car seats recording HR [24] broadening the sensor possibilities and there are new ways of analysing data making use of the same parameters as in this PhD. Opposed to recording methods using body posture or pressure distribution which are linked to discomfort, this PhD's experiments describe HRV parameters that are related to comfort.

To our opinion, the best way to study comfort and discomfort is a combination of measuring and using questionnaires. The measuring can be done at moments when interference in the study is not desirable, to gain background information and objectively compare situations on differences. The questionnaires or interviews are needed as comfort is by itself a subjective phenomenon.

Final Statement

Physical entities can predict comfort, and observing the interaction or human body effects like HRV can predict comfort as well. Additionally, there are good questionnaires available for many situations for recording comfort. Designers can use these methods to create a better functional aircraft interior which then increases passenger comfort.

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Delft, March 2021
Shabila Anjani

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About the Author

Curriculum Vitae

Shabila Anjani was born in Jakarta on July 29th 1992. She graduated from 34 Senior High School Jakarta in 2010 majoring science and continued her bachelors in Industrial Engineering, Universitas Indonesia. She graduated with a Bachelor of Engineering degree in 2014 (cum laude) with a bachelor thesis titled *Maximum Capacity Analysis of Soekarno-Hatta International Airport's Runway*.

She continued her studies with dual master program, graduating in 2015 with a cum laude Master of Engineering degree from Industrial Engineering, Universitas Indonesia and a Master of Business Administration degree from Industrial Management, National Taiwan University of Science and Technology. Her master research was titled *Evaluation of Car Icons Using a Decision Tree.*

After graduation, she started an academic career as a lecturer as well as a researcher at Industrial Engineering, Universitas Indonesia. In 2017, she started her PhD in Industrial Design Engineering, Delft University of Technology. During her PhD she did various research focusing on comfort in airplanes as well as other vehicles.

List of Publications

Publication Part of This Thesis

Chapter 2. Interaction

i) Anjani S., Li W., Vink P., Ruiter I. (2019) The Relationship of Space Experience and Human Anthropometric Sizes in Aircraft Seat Pitch. In: Bagnara S, Tartaglia R, Albolino S, et al (eds) Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018). Springer, Cham, Florence, Italy, pp 504–511

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Chapter 3. Human Body Effects

Anjani S., Song Y., Vink P. (2020). HRV, seat, comfort and discomfort relationship over time. Manuscript submitted for publication

Chapter 4. Perceived Effects

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Chapter 5. Application

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ii) Anjani S., Song Y., Vink P. (2021) Designing a floor plan using aircraft seat comfort knowledge by aircraft interior experts. Work 68:s1. https://doi.org/10.3233/WOR-208001

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