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Design and analysis of experiments aimed at improving the aircraft seat comfort for young and elderly passengers

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Symbol	Meaning
$\boldsymbol{V}$	Number of Treatment and levels in Latin Square
μ	Mean Value
T	Treatment
C	Control
$\pm\delta$	treatment parameter depending on whether T or C is used in the first period of cross over design.
$+(\boldsymbol{\delta}+\boldsymbol{\gamma})$	Treatment parameter in the second period
$\pm\rho$	Carry over effect
Δ	Target parameter
R	Response variable
$\boldsymbol{\theta}$	Parameter to be estimated
η_i	Linear Predictor
$g(\mu_i)$	Link Function
m	Number of response categories
$\mathbf{u_i}$	Random effect
$\hat{\sigma}_u^2$	Estimated variance of Random effect
σ^2	Residual variance
$\mathbf{h^{-1}}$	Inverse Link Function
$\boldsymbol{\pi}$	Uncertainty parameter
ξ	Feeling parameter
$\boldsymbol{\beta}$	Parameter vector of subject covariates related to the uncertainty component
$\boldsymbol{\gamma}$	Parameter vector of subject covariates related to the feeling component
$\boldsymbol{\nu}$	Parameter vector of object covariates related to the uncertainty component
$\boldsymbol{\eta}$	Parameter vector of object covariates related to the feeling component
y_i	Subject Covariates related to uncertainty
w_i	Subject covariates related to feeling
x_k	Object covariates
$\mathbf{F_p}$	Force acting perpendicularly on the surface
$\mathbf{F_s}$	Force acting parallel the surface

Glossary

ANOVA: analysis of variance

BMI: Body Mass Index

BPD: body part discomfort

CLM: Cumulative Logit Model

CLMM: Cumulative Logit Mixed Model

CR-10: 10 points category ratio scale

CUB: Combination of Uniform and Binomial Model

(Dis-)comfort: comfort and discomfort

DOE: Design of Experiment

EMG: electromyography

GCR: General Comfort Rating

GLM: Generalized Linear Model

ICC: Intra-Class Correlation

IT: ischial tuberosities

MPP: mean peak pressure

VAS: visual analogue scale

ABSTRACT

Population ageing is becoming a global phenomenon. According to the United Nations report World Population Ageing, *“the number of older people aged 60 or over was about 202 million in 1950, accelerated to 841 million in 2013, and will triple by 2050”*. The contextual implementation of active and healthy ageing policies, modifying the expectation, quality and lifestyle of the elderly, is offering opportunities and challenges on various aspects of daily life and health management: among the various positive aspects, this has determined an increase in mobility for recreational purposes and therefore an increasing complexity of the needs connected to it. These changing needs must be considered in the design of transport environments to ensure dignity and autonomy for passengers, in accordance with the policy of non-discrimination promoted by European regulations for users with reduced mobility (EC n.1107/2006).

In 2017, following a positive trend begun in 2010, passengers who used air transport for their journeys to or from European Union countries exceeded the record figure of one billion for the first time. In 2018, according to Eurostat data, air traffic increased by a further 6% at European level, involving 1 billion 106 million passengers. In this European scenario, Italy is the fifth country in the EU ranking for the number of transported passengers, preceded in order by the United Kingdom, Germany, Spain and France, and is even in second place, preceded only by Spain, if referring to the transport of passengers on the national territory. In 2019, passengers transited through the 39 Italian airports monitored by Assaeroporti amounted to 193 million, i.e. 7.4 million more than the previous year equal to +4%, in line with the positive trend of previous years; among them, 19% on average were between 55 and 64 years old and 12% over 65 (Istat, May 2020). Together with the diversity of passenger population, it should be emphasized the change of their needs, helped by rapid technological development that allows passengers to carry out various activities from the comfort of their seats.

Therefore, the heterogeneity of new transport needs makes it necessary to adopt an inclusive design approach, aimed at designing and implementing products that are accessible and usable by the largest number of potential users.

The proposed research aims to support the ergonomic design of aircraft interiors in order to improve the quality of the mobility experience of both elderly passengers and passengers with reduced mobility. Specifically, the research started from the generation phase of their concept and went through the development of experimental protocols and methods for the evaluation of different design solutions and the continuous monitoring of postural comfort through temporal analysis of data collected by pressure and movement sensors.

The research activity focused on the aspects of passive mobility, that is the context in which the air passenger operates (although the same can be extended to other contexts different from air transport, such as rail, sea or road transport):

1. identification of strategies and methods for assessing the accessibility and passenger comfort;
2. characterization of critical postural parameters to maximize passenger comfort;
3. elaboration of experimental protocols aimed at validating the feasibility of the proposed design solutions through experimental campaigns in real life.

The activities related to the first point were carried out through an extensive analysis of the specialized literature concerning the analysis of (dis-)comfort both in aircraft environment and transport in general. The investigation then focused on methods for assessing the accessibility and (dis-)comfort of the passenger seat. Literature studies have focused most of the research activity on the evaluation and analysis of the experiences of young and healthy passengers who are able to move independently. Each study adopted different strategies preventing both comparison and generalization of results. Indeed, recent literature reviews have highlighted the need to develop methodologies for collecting and analyzing comfort data producing statistically significant evidence to provide diagnostic information to all stakeholders

The activities inherent to the second point concerned the formulation of an evaluation strategy suitable to identify the needs of passengers, both young and old, and the critical features of the seat on which to intervene to maximize the comfort experience with respect to the functional characteristics of interest. These strategies were implemented during several experimental campaigns which, as described in the third point, involved the establishment of specific experimental protocols that allowed for replicability of the experimental tests and reliability of the results.

In order to carry out the outlined activities, it was necessary to make use of different skills and tools. First of all, the experimental tests were designed with respect to appropriate methodologies for planning experiments (i.e. Design of Experiments, DOE) in order to minimize the number of tests and the impact of the main noise factors such as anthropometric characteristics of potential users, time and duration of the test.

Two types of data were collected: subjective and objective measures. The collected subjective measures involved directly the selected sample who carried out an assessment of personally perceived (dis-)comfort, usability and accessibility (ease of ingress/egress) with respect to the conditions tested each time. The selected sample of participants was always sufficiently representative of the population of interest and was trained in advance to perform the test. To detect subjective measures, survey instruments such as questionnaires or checklists existing in the literature or specially elaborated and previously validated were used.

The objective measures (i.e. pressure at the seat-occupant interface) were obtained using different instruments: mats equipped with sensors for both seat and backrest were used for the detection of pressures at the seat-occupant interface.

RIASSUNTO

L'invecchiamento della popolazione sta diventando un fenomeno globale. Secondo il rapporto delle Nazioni Unite-Invecchiamento della popolazione mondiale- *'il numero di anziani di almeno 60 anni era circa 202 milioni nel 1950, è cresciuto fino a 841 milioni nel 2013, e triplicherà nel 2050'*. La contestuale attuazione di politiche di *active and healthy ageing*, modificando l'aspettativa, la qualità e lo stile di vita degli anziani sta offrendo opportunità e sfide su vari aspetti della vita quotidiana e della gestione della salute: tra i vari risvolti positivi ciò ha determinato un aumento della mobilità per fini ricreativi e quindi una crescente complessità delle esigenze ad essa connesse. Di tali mutate esigenze è necessario tener conto nella progettazione degli ambienti di trasporto per garantire dignità ed autonomia ai passeggeri, in accordo alla politica di non discriminazione promossa dai regolamenti europei per gli utenti con ridotta mobilità (EC n.1107/2006).

Nel 2017, sulla scia di una tendenza positiva iniziata già nel 2010, i passeggeri che hanno utilizzato il trasporto aereo per i loro spostamenti in partenza o in arrivo nei Paesi dell'Unione europea hanno superato per la prima volta la quota record di un miliardo. Nel 2018, in base ai dati di Eurostat, il traffico aereo è aumentato di un ulteriore 6% a livello europeo, coinvolgendo 1 miliardo e 106 milioni di passeggeri. In tale scenario europeo l'Italia è il quinto Paese nella graduatoria Ue per numero di passeggeri trasportati, preceduta in ordine da Regno Unito, Germania, Spagna e Francia, e si colloca addirittura al secondo posto, preceduta solamente dalla Spagna, se si fa riferimento al trasporto di passeggeri sul territorio nazionale. Nel 2019, i passeggeri transitati nei 39 scali italiani monitorati da Assaeroporti sono stati 193 milioni, ovvero 7.4 milioni in più rispetto all'anno precedente pari al +4%, in linea con il trend positivo degli anni precedenti, di cui il 19 % in media con un'età compresa tra i 55 e i 64 anni e il 12% di età superiore a 64 anni (Istat, maggio 2020). Inoltre sono mutate anche le esigenze dei passeggeri favorite da un rapido sviluppo tecnologico che permette di svolgere diverse attività stando comodamente seduti. Pertanto l'eterogeneità delle nuove esigenze di trasporto rende necessario adottare un approccio progettuale inclusivo, ossia volto alla progettazione e alla realizzazione di prodotti accessibili e utilizzabili dal maggior numero di potenziali utenti.

La ricerca proposta ha l'obiettivo di supportare la progettazione ergonomica degli interni di aeromobili per migliorare la qualità dell'esperienza di mobilità dei passeggeri, con un'attenzione anche ai passeggeri anziani e con ridotta mobilità, attraverso protocolli sperimentali e metodi per la valutazione, soluzioni progettuali alternative e il monitoraggio del comfort posturale effettuato mediante analisi spazio-temporali dei dati rilevati da sensori di pressione e movimento.

L’attività di ricerca si è focalizzata sugli aspetti di mobilità passiva, ovvero il contesto nel quale si trova ad agire il passeggero aereo (ma lo stesso discorso può essere esteso ad altri contesti diversi da quello aereo come quello ferroviario o marittimo). L’attività di ricerca ha avuto come obiettivi:

1. l’identificazione di strategie e metodi per valutazione dell’accessibilità e del comfort della postazione del passeggero;
2. la caratterizzazione temporale di parametri posturali critici per massimizzare il comfort del passeggero;
3. l’elaborazione di protocolli sperimentali volti a validare la fattibilità delle soluzioni progettuali proposte attraverso campagne sperimentali in reale.

Le attività inerenti il primo punto sono state realizzate attraverso un’ampia analisi della letteratura relativa sia all’analisi del (dis-)comfort in ambiente aereo che nel trasporto in generale. L’indagine si è poi focalizzata sui metodi per la valutazione dell’accessibilità e del comfort della postazione del passeggero. Gli studi di letteratura si sono principalmente concentrati sulla valutazione e l’analisi delle esperienze dei passeggeri giovani, in salute e capaci di muoversi in maniera autonoma ed indipendente. Ciascuno studio ha adottato strategie di indagine differenti impedendo sia la comparazione sia la generalizzazione dei risultati. Infatti, recenti studi di letteratura hanno messo in luce la necessità di sviluppare metodologie di rilevazione e analisi dei dati di comfort che producessero evidenze statisticamente significative al fine di fornire informazioni diagnostiche a tutti gli stakeholder.

Le attività inerenti il secondo punto hanno riguardato la formulazione di una strategie di valutazione che ha consentito di identificare i bisogni dei passeggeri, sia giovani che anziani, e le caratteristiche critiche del sedile sulle quali intervenire per massimizzare l’esperienza di comfort rispetto alle caratteristiche funzionali d’interesse.

Tali strategie sono state introdotte durante diverse campagne sperimentali che come descritto al terzo punto hanno richiesto la costituzione di specifici protocolli sperimentali che hanno consentito la replicabilità delle prove sperimentali e l’affidabilità dei risultati.

Per condurre le attività definite è stato necessario avvalersi di diverse competenze e diversi strumenti. Innanzitutto, le prove sperimentali sono state progettate secondo opportune metodologie statistiche di pianificazione degli esperimenti (Design of Experiments, DOE) al fine di ridurre al minimo il numero di prove e l’influenza dei principali fattori di disturbo quali ad esempio le caratteristiche antropometriche dei potenziali utenti, il tempo e la durata della prova. Sono state rilevate due tipologie di dati: misure soggettive e misure oggettive. Le misure soggettive rilevate hanno previsto il coinvolgimento diretto del campione selezionato di partecipanti che ha effettuato una valutazione di (dis-)comfort, usabilità e accessibilità (facilità di accesso) personalmente percepite rispetto alle condizioni di prova testate di volta in volta. Il campione di partecipanti selezionato è sempre stato sufficientemente rappresentativo della popolazione di interesse ed è stato preventivamente preparato ad eseguire il test. Per rilevare le misure soggettive, sono stati utilizzati strumenti di rilevazione come questionari o *checklist* esistenti in letteratura o appositamente costruiti e preventivamente validati.

Le misure oggettive, ovvero la pressione all'interfaccia sedile-occupante, sono state rilevate mediante diversi strumenti: le pressioni all'interfaccia sedile-occupante sono state rilevate attraverso dei tappetini muniti di sensori sia per il piano di seduta che per lo schienale.

CHAPTER 1

Over the last years, passenger air traffic has been constantly increasing with 3.7 billion passengers carried by the world's airlines, supporting an increase in the passenger fleet of aircraft over 100 seats to over 19.000 aircraft, and also supporting record levels of deliveries from the manufacturers (Airbus, 2017–2036). Even though the COVID-19 pandemic has crippled global air travel with many travel restrictions, people are interested to travel again when they will be allowed to (Borko et al., 2020).

Indeed, assuming that the vaccine is widely made available for travelers by Summer 2021 (Eurocontrol Statfor 2020) and the annual growth rate for global passenger air traffic from 2020 to 2039 equals 4% (Statista 2020), 8 billion transit passengers are estimated in 2039 (Figure 1).

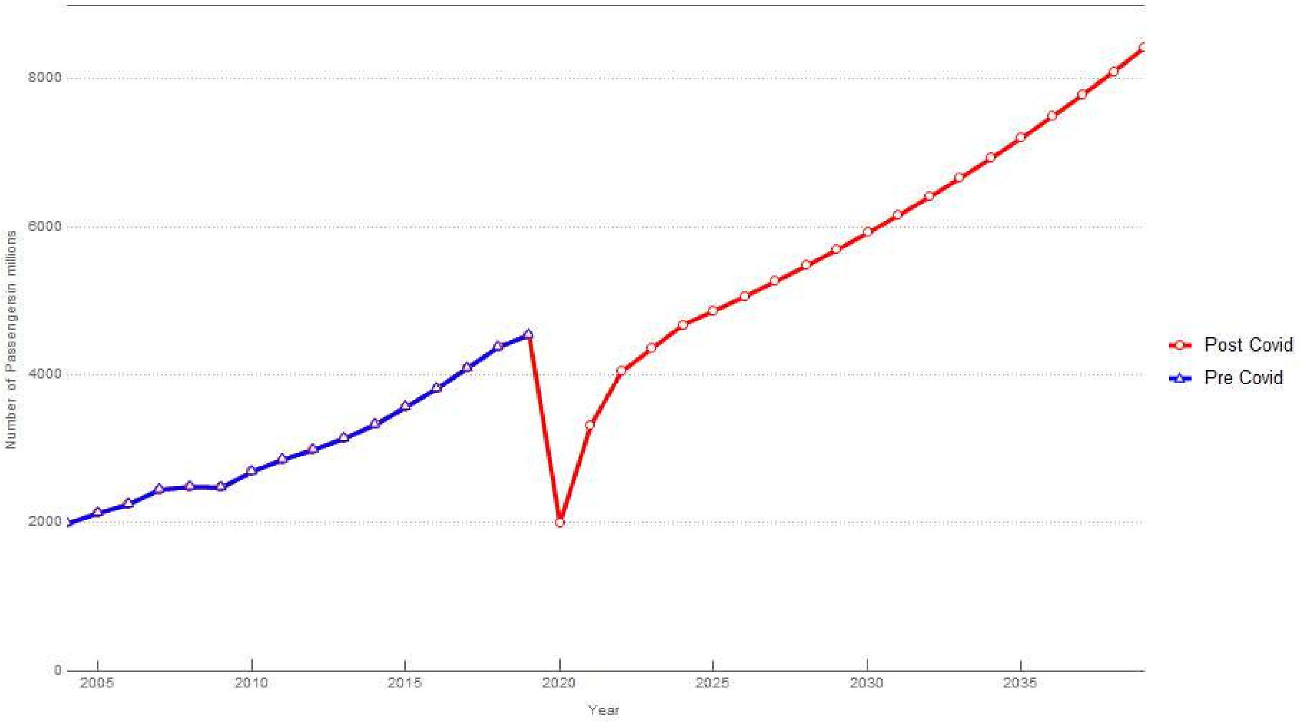

Figure 1. Forecast of global air passengers (2004-2039).

In order to attract more passengers, airlines differentiate their offer through various levels of design, services and prices.

Several studies (Richards, 1980; Vink and Hallback., 2012) showed that improving the sense of comfort associated with a trip results in an increase in the proportion of passengers who wish to use the same aircraft on future occasions. Brauer (2004) investigated convenience, comfort and cost to find means through which an airline could attract more passengers and still profit without compromising too much on its expenses. The results revealed that a margin of 1% in profit, gained by 1% increase in the number of passengers, is equal to a 14% cut of maintenance costs. Brauer also showed that beyond criteria such as point-to-point trip, time and price, around 35% of passengers base their selection on comfort, past experiences and delays. Furthermore, passengers are shown to be willing to pay extra for enhanced in-flight service provision and level of comfort (Balcombe et al., 2009; Brauer, 2004; Hiemstra-van Mastrigt et al., 2017) indeed comfort is shown to be the main factor to passenger's acceptance of transportation systems (Tan et al. 2010).

In this scenario, since the aircraft seat is rated as the most unsatisfying aspect of flying, sitting comfort improvement can provide a concrete opportunity for airlines to improve customer's satisfaction and loyalty and thus gain competitive edge in aircraft industry (Dolnicar, 2011; Vink, 2016).

1.1 Comfort and Discomfort: Definitions and Conceptual Models

The comfort concept is not simple to define because it involves many aspects and it depends on several factors.

The word comfort is derived from the Latin word *confortare*, meaning *to strengthen much*. In German Van Dale dictionaries comfort is described as *no pain, well-being*. The Webster's Dictionary defines comfort as a *state or feeling of having relief, encouragement and enjoyment*. The Oxford Dictionary defines it as *a state of physical ease and freedom from pain or constrain*.

In the field literature, Slater (1985) attempted a more scientific definition: *a pleasant state of physiological, psychological and physical harmony between a human being and the environment* and Richards (1980) defined the comfort *a subjective feeling of well-being*.

Dumur, Bernard, and Boy (2004) suggested four points of view towards comfort: 1) psychological comfort is a state of quiet enjoyment, free from worry and disappointment with regards to basic human needs (e.g. food, security, etc.), it entails aesthetics comfort (satisfying one's taste for forms, sound, smell, etc.), socialization comfort (incorporating the need for social relationships as well as privacy) and conformity (the sense of belonging to a group); 2) physical comfort is the state of being free from issues pertaining to physical, physiological and biomechanical states; 3) sociological comfort is related to one's ethnic and social class whereas 4) comfort technological point of view refers to those material inputs from the environment providing pleasurable sensations.

The notion of comfort naturally entails discomfort: it is a multifaceted construct influenced by several factor that is not merely the opposite of discomfort.

Hertzberg (1985) postulated that comfort and discomfort are not two different states of consciousness, but *that there is only one, discomfort, and that 'comfort' is only the absence of discomfort.* According to this definition of comfort and discomfort Shackel et al. (1969) used a linear scale to select an appropriate office chair for workers. The idea behind these studies is that the comfort has not necessarily positive effects (Branton, 1969) and therefore the aim becomes to design a product (or a service) that allows to live an experience of discomfort absence (Bishu et al., 1991). Alternatively, to the idea of a discrete nature of comfort, some researches defines comfort and discomfort as two opposites of a continuous: a bipolar phenomenon whereby comfort is positioned at the extreme positive end and discomfort at the extreme negative end of a continuum with a neutral point at the center of the scale. This assumption derives from the idea that people, frequently and in a natural way, are able to order their own subjective experiences in reference to a continuous that goes from positive to a negative extreme (Richards, 1980). The study of Dijksterhuis et al. (2009) consider that generally users are unaware of the characteristics of the environments in which they operate, which generate positive experiences. This implies that the concept of comfort is not innate in human: the user does not distinguish between comfort and discomfort but rather he/she is able to perceive what disturbs his/her experience (i.e. discomfort). It follows that the absence of discomfort does not automatically translate into comfort: the comfort can be perceived only when the user experiences more than what he/she is expected.

The strongest research supporting a non-linear relationship between comfort and discomfort came from Zhang and Helander (1992) and Zhang et al. (1996). These studies distinguish three different comfort states:

1. ***discomfort***, linked to physical environment and responsible for physical pain;
2. ***no discomfort*** resulting in the absence of discomfort or pain which is rarely perceived since the user, basically, in case of no discomfort does not claim to have experienced anything;
3. ***comfort,*** typically connected to an experience of extreme wellness expectations and then connected to the luxury, relaxation, physical and mental refreshment.

In many cases the user is not able to assign a rating of comfort while in specific conditions he/she is able to give a discomfort rating.

Despite the variety of definitions, it is basically accepted that the issue of evaluation and analysis of comfort and discomfort (hereafter (dis-)comfort) experience is very complex: it is the result of a subjective experience, derived by an interaction with the environment and influenced by multiple heterogeneous factors (physical, psychological and physiological).

In the Editorial of Vink and Hallback (2012), there is a need to propose a suitable and complete (dis-)comfort model. The authors starting from a literature overview for suggesting their model, highlighted 5 main topics: (1) the sensory input (De Korte et al., 2012), defined as the process from the environment towards the feeling or sensory experience; (2) how the activities affect the comfort measurement (Groenesteijn et al., 2012); (3) the importance of the difference in how comfort is experienced in different body regions (Franz et al., 2012; Kong et al., 2012); (4) the effect of product contour on comfort experience (Noro et al., 2012) and finally (5) the relationship between the discomfort and the physical loading (Lee et al., 2011; Zenk et al., 2012), demonstrating that discomfort also has value in connection to musculoskeletal loading. Several theoretical models have been proposed in the scientific literature with the aim of providing tools to interpret the genesis of the (dis-)comfort experience.

Building upon the model by Helander and Zhang (1997), the theoretical model of (dis-)comfort and its underlying factors by De Looze, Kuijt-Evers, and Van Dieën (2003) distinguishes three levels: human, seat and context (Figure 2). At context level, the physical environment has an influence on sitting discomfort, whereas at seat level, aesthetic design can also influence sitting comfort.

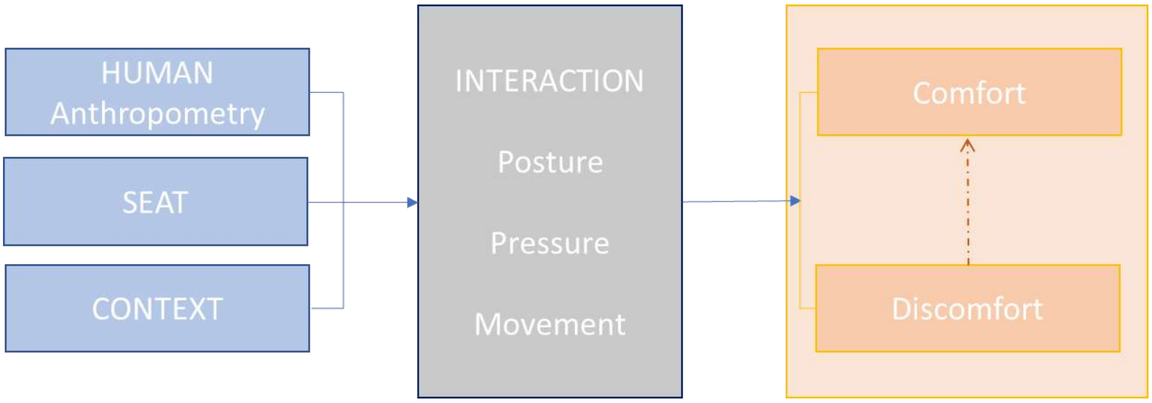

Figure 2. Discomfort model proposed by De Looze et al. (2003).

Moes (2005) deals about a specific case about seat design and describes that if a person uses a seat with a specific purpose, the interaction (I) arises (see Figure 3) and, for example, it can consist of the pressure distribution of the contact area between person and seat. An interaction results in internal body effects (E), such as tissue deformation or compression of nerves and blood vessels. These effects can be perceived (P) and interpreted, for instance as pain. The next phase is the appreciation (A) of the perception. If these factors are not appreciated, it can lead to feelings of discomfort (D) and, in order to improve the experience, you need to work on the interaction or to set a different environment by acting on its factors.

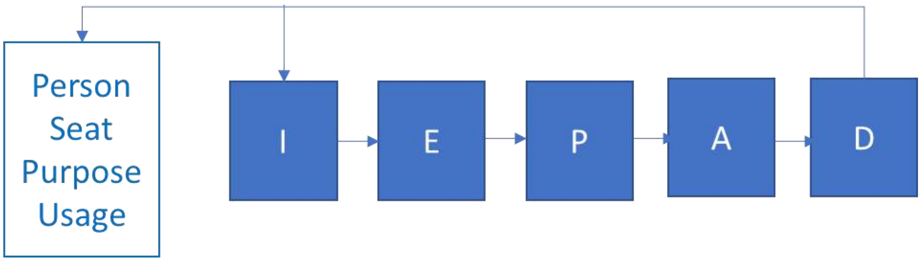

Figure 3. Discomfort model proposed by Moes (2005).

Vink and Hallbeck (2012) have modified the discomfort model proposed by Moes (see Figure 3) defining 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*. The (dis-)comfort model proposed by Vink and Hallbeck (2012) simplifies the steps that influence the (dis-)comfort experience (see Figure 4) making clear the genesis of this experience. Specifically, the interaction caused by a contact (also a not-physical contact, e.g. a signal; De Korte et al., 2012) between a product (e.g. the seat) and the passenger starts in the environment (e.g. aircraft) where the passenger is doing a specific task (i.e. activity) and this interaction can result in internal human body effects (e.g. changes in human sensors, tactile sensations, body posture change, blood flow changes and muscle activation). Moreover, the perception effects are influenced not only by the human body effects but also by expectations so that the final outcomes may be feelings of (dis-)comfort or no feelings. This research work is based on the (dis-) comfort model proposed by Vink and Hallback (2012).

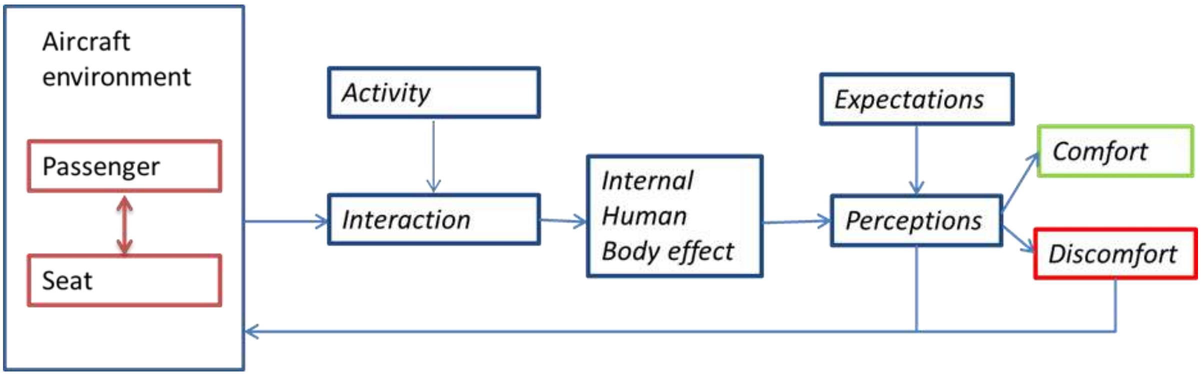

Figure 4. (Dis-)comfort Model (redraw from Vink and Hallbeck, 2012).

1.2 The passenger comfort experience

The (dis-)comfort passenger experience is described in relation to personal emotions (perceptions) and feelings of relaxation and wellbeing (Vink et al., 2005; Zhang et al. 1996) in case of comfort, stress or physical pain in case of discomfort. Perceptions are more or less automatic responses of pleasure or displeasure following the evaluation of the outcomes of an event based on passenger needs or concerns (Frijda, 1986; Desmet & Hekkert, 2007). Positive perceptions (e.g. positive feelings) are elicited when it is found, using a seat for example, the benefits for personal needs (e.g. not experiencing pressure points at the buttocks) and negative perceptions are due to harmful event (Frijda, 1986). Perceptions are defined as internal and mental states in reaction to ongoing situations that are perceived good or bad (Ortony et al., 1987); they are distinguished from other affective states, such as moods, in that they are focused on something/someone (e.g. afraid of someone, anxious about something, etc.), concern the present time (not future or past times) and are thus short-term reactions (Clore et al., 1994). It is essential to differentiate mood (an example of a mood is being depressed) from perceptions. The mere presence of mood could impact the type or intensity of perceptions involved.

Passenger comfort studies can be categorized into two principal groups. The first one explores the holistic experience of passengers associated with a feeling of (dis-)comfort. That is the overall comfort of the flight, influenced by all the cabin elements and the in-flight services as well as the psychological or social inputs in the context. Dumur et al. (2004) discussed 4 factors to demonstrate the overall comfort of passengers in modern aircrafts:

1. the passenger area, namely the experience of privacy whereby one could pursue the desired activities;
2. the health factor, focused on physical wellbeing and the absence of health issues;
3. the community factor, focused on the shared and social experience of passengers in the cabin;
4. the aesthetic-economical factor, concerned with the enjoyment and pleasure delivered to passengers by the cabin environment at a given cost.

The second group of passenger comfort studies deals with (dis-)comfort related to specific features of the aircraft interiors such as seat, noise, temperature, pressure, vibration. Vink et al. (2005) classified them into:

- thermal comfort;
- acoustic comfort;
- visual comfort, concerned with the design aspects of the cabin interior;
- physical comfort, related to seating and posture, physical loading, foot pressure, etc.

This thesis focuses on the second group of studies and specifically on **seating comfort**, which will be hereafter discussed in length.

1.2.1 Seating Comfort

The seating comfort is not only an ergonomic goal. Nowadays, the growing demand by users represents an important sale opportunity for seats manufacturers in different areas: automotive, aircraft and transport in general.

The field literature on human factors and ergonomics has widely investigated the topic of comfortable and optimized seating, focusing mainly on office (e.g. Bazley et al., 2015; Groenesteijn, 2015; Van Dieën et al., 2001) or automotive (e.g. Franz, 2010; Zenk et al., 2006) seats whereas scientific papers on passenger seats in public transport are much less common (e.g. Lee et al., 2009; Park et al., 2014).

Comfort experience exists only in the interaction between passenger and seat within a specific context (Vink and Hallbeck, 2012; De Looze et al., 2003). This means that the characteristics of the potential passenger population (not only the number but also the diversity of air passengers increases), the activities they perform (different sitting postures are associated with different tasks and activities) and the aircraft environment in which they are seated should be taken into account when designing a seat (Ahmadpour, 2014).

Although the trend of increasing height has been gradually slowing or stopping in many populations, there is a strong tendency towards increasing weight and obesity in many European countries and the

USA (Komlos and Baur 2004). Another trend is the ageing of the population. Until 2050 the share of people aged 65 and above will increase from about 20 per cent today to about 30 per cent. The age group share of children aged 0 to 14 remains stable over time whereas the working age population (ages 15 to 64) is predicted to shrink from 66 per cent today to 57 per cent in 2050 and the over 80 is predicted to increase from 6 per cent today to 12 per cent in 2050 (DATASET, 2050). Population aging is happening in most of the world's metropolitan cities and the proportion of elderly adults is predicted to increase significantly in the coming decades.

This rapid growth of elderly populations may lead to serious transport issues when their mobility is compromised by the unavailability of transport services. At same time, elderly people are willing to fly and can afford time and money.

Furthermore, a revolution in Information Communication Technologies devices, applications and networks also introduces a larger variation in activities that passengers perform while traveling. It is expected that the use of small handheld devices, such as smart phones, e-readers and tablet PCs, will continue to increase, thereby increasing the number of passengers that use these devices (Hiemstra-Van Mastrigt, 2015).

With regard to the internal environment of the aircraft, although the comfort of new aircrafts is rated higher than old ones, knee space is still one of the major problems (Vink and Hallbeck., 2012), as it was in the past (Richards and Jacobson 1977). Airlines are even pushing seat capacity to the limits of the airplane design: single-aisle airliners such as the Airbus A321 already have more seats than a much larger twin-aisle airplane such as the Boeing 767-2001, limiting passenger space even more.

To attract passengers, seats could consider the cultural diversity of passengers, the change in demographics and the activities that they want to perform during travel (Hiemstra-Van Mastrigt, 2015). Several studies (Vink at al., 2007; Vink, 2016; Richards and Jackobson, 1977) have identified a significant correlation between seat comfort and legroom.

It follows that in order to enhance the experience of passenger comfort, extensive attention must be devoted to the space for legs in the design of the seat layout (Anjani, 2021). An increase of legroom can be obtained by intervening on two different seat design parameters: the seat pitch and the thickness of the backrest (back thickness). An increasing of the pitch is certainly responsible for a widening of the space for the legs; for this reason many passengers, the so-called pitch watchers, are oriented towards the choice of an airline after consulting the pitch values of the corresponding seats. The thickness of the backrest is a further design parameter which can be modified for the purposes of comfort: it influences the space that becomes available between hips and knees. So, for example, a pitch of 33 inches combined with one of 3 inches backrest thickness provides less space than a pitch of 31 inches often combined with a backrest of 1 inches. However, every year, passengers are traveling in restricted postures, being not able to perform the activities they want and risking health problems such as back pain (Helander and Quance, 1990; Burdorf et al., 1993) and neck pain (Ariëns et al., 2001).

It should also be considered that many aspects which have a significant impact on the comfort are not covered in the ergonomic guides because they are not easily quantifiable such as the aesthetic appearance, the cushion characteristics, the three-dimensional shape of the seat, the support provided for different parts of the body and the ability to allow posture changes.

Researchers agree that seating comfort can only be improved and optimized if the basic parameters that influence it are known and specific measurement techniques are defined (Adler, 2007).

1.2.2 Literature Review on elderly passengers (dis-)comfort experience

The improved quality of life, the greater control of chronic disease and financial stability after retirement have resulted in an increase in the number of trips among the elderly population. Generally, the elderly population who travel have been traveling since their youth and age is not a restriction for traveling (Ramos-Sesma et al., 2018).

However, the older segment of the population requires some special consideration in the design of transport environment for several reasons. There are many changes in the body that occur with the normal process of ageing, such as decreased strength, co-ordination, perceptual abilities and mobility; while an accumulation of physical changes may occur first, further psychological changes may cause related problems and specifically changes in a person level of confidence (Donorfio et al., 2009).

Mobility refers to a person ability to move from one place to another in an independent and safe way and it typically declines gradually as people age (Rantakokko et al., 2013). For the elderly, mobility is not only a crucial element of overall life satisfaction but also a prerequisite for active aging. It is essential for independence, good health and quality of life (Whelan et al., 2006; Metz, 2000; Banister and Bowling, 2004; Spinney et al., 2009). A lack of mobility can deter older people from participating in social activities, resulting in low morale, depression and loneliness (Atkins, 2001). Thus, future transport policies should prioritize the mobility of elderly populations to support their independence and thereby improve their quality of life; making the transport service procedures more accessible to elderly travelers would allow airlines and airports to benefit from meeting the demands of a growing market (Chang and Chen, 2012).

The procedure for passengers using air transport consists of three main stages: pre-travel, pre-flight and during flight; the difficulties that may occur in each stage can discourage older travelers from undertaking a trip. In the pre-travel stage, an elderly passenger may not know what services are provided during the airline ticket reservation process, such as meal service or seat selection. As for the pre-flight stage, for example, most airlines have introduced automatic ticketing and check-in kiosks and the elderly may have difficulty in using these machines; regarding airport facilities, many elderly people have problems with their sensory ability, so that they may have problems to read signs and display boards at the airport or to hear flight information announcements. During the flight, due to physical impairment, the elderly may need to go to the restroom more often and so they may prefer to sit near to the bathrooms and for the facilities to be easier to use. In addition, as cabin safety information is designed for average passengers, the elderly may not be aware of how to cope in an emergency and some actions may be beyond their physical capabilities (Chang and Chen, 2012). The elderly is more likely to have restricted physical mobility or diseases that limit movements; airlines have developed recommendations and advice aimed at helping elderly travelers, allowing them to reserve a seat and board before other travelers, offering comprehensive assistance to the elderly at airports, offering special menus aboard the flight, providing a *doctor on board* program with supplemental oxygen and responding to health-related questions regarding travel.

From a technical point of view, to ensure safety and maintain mobility, it is important that the elderly passenger can transfer in and out of a aircraft seat easily. Difficulty rising from a seat is common in older people, exacerbated by arthritis or weak proximal muscles. Lowered seat height increased back recline, posterior seat tilt and seat compressibility are all factors which can increase difficulty with seat egress. The latter two aspects of seat design may, however, also increase discomfort.

An aircraft interior should be adjusted to the needs of elderly, but research data in this area are limited. Especially, with respect to in- and egress, many studies are conducted in the automotive domain rather than in the aircraft domain, where the movements of young people are compared to those of older people. A conducted literature review focused on elderly passenger seat (dis-)comfort in a human–seat–context interaction was carried out. This literature review focused on the relationships between anthropometrics (human level), seat characteristics (seat level) and activities of passengers (context level), on perception of (dis-)comfort and how this is influenced by three variables: sitting posture, interface pressure and movement. The studies for the literature review were retrieved through a search in Scopus. The following combination of terms were searched for in article title, keywords and abstract: elderly, anthropometric characteristics, seat and context characteristics on comfort and discomfort (‘sitting comfort’, ‘sitting discomfort’ or ‘elderly passenger comfort’), influenced by posture, pressure (‘pressure distribution’, ‘pressure’, ‘maximum pressure’ or ‘pressure gradient’) and/or movement. In addition, relevant references from the selected articles were checked. Articles were included in this review only if they met all of the following criteria:

1. the paper describes an experiment with elderly or a literature review related to (dis-)comfort measurements in sitting of elderly in combination with measurements of anthropometry and/or pressure measurement;
2. the paper describes a study with young subjects compared with elderly subjects in standard sitting situations (i.e. general transport field, automotive field or aircraft field).

The main results are reported in Table 1. What emerged from the literature review is that most of the studies involving elderly people were developed in the automotive field with the aim of investigating how vehicle ingress and egress strategies impacted vehicle design and how interventions could be made to improve driver/passenger safety and comfort. A comparative study (Lijmbach, et al., 2014) was developed in aircraft field between young and elderly passenger, in order to evaluate the ingress and egress strategy in different seat pitch conditions.

Table 1. Main Results of literature review carried out during the research study

Reference	*Research area*	*Variables*	*Method*	*Summary of the study*
El Menceur, M.O.A et al., 2008	Automotive	Joint Angles Ingress/Egress Strategies	Experimental Study	The objective of this paper was to identify the ingress/egress movement strategies adopted by a heterogeneous population composed of young and elderly persons with or without prostheses, for four vehicles representing a wide range of the vehicles currently available on the market. 164 ingress and egress movements were recorded. The different movements were stored in a database and then reconstructed by using a humanoid model. Two main families of ingress/egress movements were identified: one-foot ingress (or egress) movements in which the subject balanced in the left foot, and two-foot ingress (or egress) movements in which both feet were used. There were eight separate ingress/egress movement strategies identified: five for ingress and three for egress. We confirmed the three ingress strategies and the one egress strategy identified by Andreoni et al. (1997). There was no specific strategy for a specific population, thus young able-bodied people entered or exited a vehicle in the same manner that elderly or disabled people did and vice versa. However, there were some dominant trends in both ingress and egress strategies, mainly in able-bodied young and elderly people. Disabled people showed no special preference for any strategy. The vehicle geometries did not appear to influence the choice of strategy, and thus the strategy distribution is equitable between the four vehicles, despite the considerable differences between the geometries
Crizzle et al., 2014	Automotive	Vehicles Ingress/egress Strategies	Systematic review	Systematic review to identify ingress and egress strategies with the aim to safer vehicle design that reduce fall risk and improve comfort. The results of the present research synthesis show that participants reported challenges with doorway height, sill height during ingress and egress, as well as will width during egress. There are also various ingress and egress strategies employed by

				drivers. However, ingress and egress strategies did not differ significantly by sample characteristics (i.e., age, height) or vehicle type.
Causse et al., 2009	Automotive	Vehicles Ingress/egress Strategies Discomfort	Experimental Study	The aim of the study is to propose a suitable experimental protocol for a dynamic analysis of car ingress/egress motion. First, two preliminary studies based on video analysis are presented to identify the main interactions between the driver and the car and the main design parameters affecting driver discomfort. Subsequently, an experimental protocol allowing the full dynamic analysis of the car ingress/egress motion is proposed and applied to a pilot study. The pilot study aims to verify the feasibility of the proposed experimental protocol by comparing two car configurations tested by two different individuals.
Dufour and Wang, 2005	Automotive	Discomfort analysis	Study in Virtual Environment	The study present a model through the introduction of the new concept of "neutral motion" and show how it can be used for discomfort modeling in the context of restricted motion. In this paper, it present a generalized approach for assessing discomfort of complex movement. In order to define the function of joint discomfort, they introduced the concept of neutral movement which is an extension of "neutral or less bothersome posture".
Lijmbach, et al., 2014	Aircraft	Ingress/Egress Discomfort Anlysis	Experimental Study	Analysis of the differences in the strategies adopted by elderly and young people when entering and exiting the passenger seat in an airplane environment. Experiments conducted in a mock-up analyzing video recordings of entry and exit in seat rows. Results show that the elderly take significantly longer to enter and exit, especially for the seat not located in the aisle. Seniors more often support themselves by touching armrests and seat backs. The entry and exit of people with reduced mobility, such as the elderly, could be improved to provide the proper support, perhaps by redesigning the seats or/and assigning them special seats.
Kyung and Nussbaum, 2013	Automotive	Comfort/Discomfort analysis Pressure Measurements	Experimental Study	The study was conducted in which a total of 22 younger and older participants completed six short-term driving sessions. Three subjective ratings (comfort, discomfort and overall) were

				obtained, along with 36 driver–seat interface pressure measures, and were used to assess differences and similarities between the two age groups. For both age groups, localised comfort ratings were more effective at distinguishing between driver seats and workspaces. Older individuals appeared to be less sensitive to discomfort than younger individuals. Across age groups, two distinct processes were used in determining whole-body comfort and discomfort perceptions based on localised comfort/discomfort perceptions. Whole body discomfort levels were largely affected by lower back discomfort in the younger group versus upper back discomfort in the older group. Four specific pressure measures at several body regions differed between the age groups, suggesting distinct contract pressure requirements and loading patterns among these group
Gish and Vrkljan, 2018	Automotive	Phenomenology of Ingress/egress mouvment	Observational study	This study examines the embodied realities and sensory experience of vehicle ingress and egress from the point of view of older drivers. In-depth interviews were conducted with 15 women and three men, aged 57-81, and followed by ride-a-longs whereby the researcher observed participants in interaction with their automobile. It is argued that older drivers acquire a sensory auto-biography of incorporated bodily memory regarding vehicle morphology and texture in their past and current life, which informs embodied capacities of movement, awareness, and response relative to practical knowledge about what is attainable (or unattainable) for a sensuous older body. Through reflective and reflexive engagement with the sensory realm and material world, participants report structuring their lives through the haptics of touch, adoption of somatic rules, consumerist practices, as well as, specialized bodily movements and footwork sequences to ensure safety and comfort when using their automobile.
Cristiano et al. 2018	Automotive	Ingress/egress Subjective eveluations	Experimental Study	To evaluate how a specific seat design can facilitate ingress/egress movements. A prototype seat, which incorporates a roto-translation and automatic system to assist older people with

				ingress/egress movements, was designed. The aim of the study is to evaluate the prototype seat through subjective (i.e., interviews and checklists) and objective (i.e., biomechanical variables) measures in order to verify its effectiveness by lowering the physical burden of the elderly during car entry/exit. 30 healthy elderly subjects over 65 years of age, including 6 with non-pathological physical limitations, were included in the study. Results showed the proposed prototype facilitates car ingress/egress by reducing both the range of trunk and knee movements and muscle fatigue while entering and exiting a vehicle. In addition, the system seemed appropriate to limit the risk of falling while on the vehicle floor.

1.3 Thesis Outline

This thesis is the result of a research project aiming at identifying efficient and effective methodological tools to support a reliable assessment of the passenger (dis-)comfort experience.

During the research project two experimental campaigns and a large survey were conducted involving young and elderly passengers. The aim of the experimental activities was to collect data for a comparative analysis of seat (dis-)comfort experiences and derive diagnostic information to improve seat design by investigating the impact of seat features and seat pitches on the passenger (dis-)comfort experience.

In the experimental campaigns designed in a controlled environment (i.e. in the laboratory or in the fuselage) subjective measures of (dis-)comfort, global and local assessments of (dis-)comfort, as well as objective measures, pressure at the occupant seat interface were collected. In the passenger satisfaction survey carried out during the celebration of 100 years of KLM and the Dutch Design Week only subjective measures of (dis-)comfort were collected.

The objective of investigating the seat features more relevant for passenger (dis-)comfort experience was pursued through:

- a designed experiment conducted in a laboratory environment aiming at comparing a classic seat (baseline) with a lightweight seat designed for regional flights;
- a passenger satisfaction survey comparing an innovative seat with a classic one.

The first experiment was conducted in a laboratory environment and involved a group of potential passengers aged between 24 and 44 years old. The experiment aimed at comparing a classic seat (baseline) against a lightweight seat designed for regional flights via both subjective evaluations of (dis-)comfort and pressure distribution at the seat-occupant interface. The research questions were: investigating the influence of experiment duration and participant gender on subjective and objective (dis-)comfort; identifying the statistical relationship between the subjective and objective (dis-)comfort;

introducing a new index for the evaluation of the comfort loss (Load comfort Loss-LCL) based on the passenger load over the seat. The adopted strategy and results of comparative experiments to assess the (dis-)comfort of aircraft seating are reported in:

- Vanacore A, Lanzotti A, Percuoco C, Capasso A, Vitolo B. Design and analysis of comparative experiments to assess the (dis-)comfort of aircraft seating. Appl Ergon. 2019 Apr;76:155-163. doi: 10.1016/j.apergo.2018.12.012.

The effectiveness of the experimental design was evaluated by verifying the impact of the noise factors, controlled during the experiments, over passenger (dis-)comfort perceptions. The adopted strategy and results are reported in:

- Vanacore A., Percuoco C., The effect of noise factors in experimental studies on aircraft comfort, in Proceedings of IES 2019- Statistical Methods for Service Quality Evaluation, Edited by Pearson, ISBN 9788891921239.

Considering the global comfort rating as the response of interest, an analysis with two different statistical modeling approaches was conducted in order to identify which passenger characteristics and seat features affected the elicitation process of the comfort ratings. The adopted strategies and results are reported in:

- Vanacore A, Lanzotti A, Percuoco C, Capasso A, Vitolo B. A model-based approach for the analysis of aircraft seating comfort. Work. 2021;68(s1):S251-S255. doi: 10.3233/WOR-208023
- Vanacore A., Lanzotti A., Percuoco C., Vitolo B. (2021) Statistical Modelling of Comfort Preferences and Uncertainty in Subjective Evaluations of Aircraft Seat Comfort. In: Black N.L., Neumann W.P., Noy I. (eds) Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021). IEA 2021. Lecture Notes in Networks and Systems, vol 221. Springer, Cham. https://doi.org/10.1007/978-3-030-74608-7_23.

A passenger comfort survey was designed with the aim to compare the (dis-)comfort of a traditional aircraft seat against the new staggered seat conceived and designed by the Engineers of TU Delft

Industrial Design Engineering for the Flying V. The Flying V is a new type of long-haul aircraft in development at TU Delft, which consumes less energy by its form (https://www.tudelft.nl/lr/flying-v/). The not traditional shape of Flying V has asked for new interior concepts. Therefore, an attempt has been made to develop aircraft interior concepts that fit in the Flying V and could improve the passenger experience. Four concepts in the mock-up were shown to the public (potential passengers) at the fair organized at Schiphol Airport hangar to celebrate KLM 100 years. A total of 1692 visitors of the mock-up provided their preference for one of the four concepts; the strategy adopted for data collection and analysis together with the results are reported in:

- Vink, P., Rotte, T., Anjani, S., Percuoco, C., & Vos, R. (2020). Towards a hybrid comfortable passenger cabin interior for the flying V aircraft. International Journal of Aviation, Aeronautics, and Aerospace, 7(1). https://doi.org/10.15394/ijaaa.2020.1431;
- Vink, P., Anjani, S., Percuoco, C., Vos, R., & Vanacore, A. (2021). A Staggered Seat is Beneficial for the Flying V Aircraft. In Congress of the International Ergonomics Association (pp. 184-190). Springer, Cham. https://doi.org/10.1007/978-3-030-74608-7_24.

In the Chapters 1 through 6 a general framework for the assessment of aircraft seat (dis-)comfort will be provided considering the studies and results available in the specialized literature. In Chapter 2, methods for data collection used in the seat comfort study are introduced. Chapter 3 illustrates the importance of statistical design of experiments, focusing on cross over design used to plan the experimental activities. Chapter 4 introduces the statistical models adopted for the analysis of subjective data. In Chapter 5, the main seat pressure indices are described. Finally, Chapter 6 illustrates fuselage experiments performed at the TU Delft with a sample of elderly passengers aged between 61 and 85 years old. During the experiments, subjective and objective (dis-)comfort data were collected at three different seat pitches (28, 30 and 32 in).

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CHAPTER 2

In the first chapter we defined (dis-)comfort and seat (dis-)comfort models, but we have not defined how to measure the (dis-)comfort experience. For this purpose, it is possible to refer to two macro categories of (dis-)comfort detection methods: subjective and objective measurement methods.

As previously highlighted, comfort is mostly a subjective experience and most research study use investigation methods, consisting of "directly asking people about how comfortable they are" in order to collect information about the passenger (dis-)comfort experience. Parsons (2000) defines subjective methods as information gathered from the user population, in which they report their impressions of a stimulus, product or event.

However, the use of subjective measures for assessing process is not always favored. Thre main arguments against the use of subjective measures can be found in the literature. Firstly, subjective measures are the result of expectations and perceptions; they have been shown to suffer from many systematic biases related to order, scale, halo-effects (Podsakoff et al., 2003) and psychological factors (Bertrand and Mullainathan, 2001; Redelmeier et al., 2003). Specifically, when the subjective measures are collected from an average user and not from a lead user, it is difficult to have an evaluation that meets the methodological requirements of robustness, repeatability, and traceability of the data. Secondly, subjective evaluations are complex constructs based on sensory characteristics and therefore difficult to relate to rational constructs. Third, subjective measures are difficult to analyze and interpret because they are often expressed by ordinal scales.

As opposed to subjective measures, there are objective measures that are quantifiable and do not depend on human perceptions. These methods offer many advantages since they allow to have data in short time, require a little sample and finally they give measures less affected by biases because it is possible to calibrate the measuring instrument. However, the main positive aspect of objective measures is that human bias interferes marginally with the measurement (Parsons, 2000). There is a strong limit for this type of measurements, that is the objective methods are indirect. In the best case, they give an indication of a passenger seating comfort, but actually they measure something else (e.g. pressure distribution, muscle activity or lumbar curvature). De Looze et al. (2003) suggest there is a benefit in integrating both objective and subjective measures to assess comfort. Shen and Galer (1993) believe objective measures should be used to support the data derived from subjective measures in regard to seat discomfort. They assert that both methods should be highly correlated; the physical measures should be predictive of the subjective measures and vice-versa. The mixed results had to determine which seat (or specific characteristics) was comfortable and had to also indicate which was the most uncomfortable.

Although many researchers support the integration of objective and subjective data, not all studies have indicated a significant correlation between objective and subjective results.

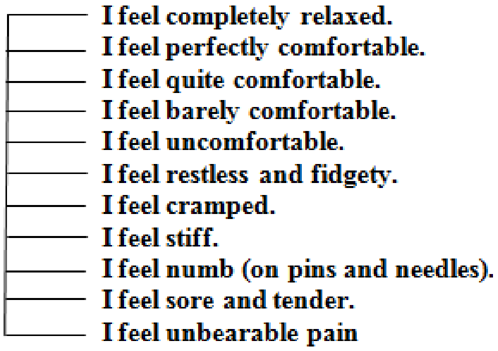
De Looze et al. (2003) describe several studies (Thakurta et al., 1995; Yun et al., 1992; Lee, et al., 1993) that used objective measures, such as pressure data and posture and movement analysis, in addition to subjective ratings on a 5 or 10-point scale to evaluate seat comfort. Yun et al. (1992) conclude that similar levels of pressure distribution on the back and buttocks area result positive in subjective levels of comfort. Thakurta et al. (1995) report that pressure distribution is associated with perceived comfort across various body regions, though no information regarding statistical significance of the relationship with subjective measures has been provided. Lee et al. (1993) also indicates no meaningful correlations between pressure distribution and local comfort when measuring seat pan comfort in sixteen different car seats (De Looze et al., 2003). Due to the inconsistencies reported regarding the relationship between objective and subjective results, the combination of objective measures with subjective ratings of (dis-)comfort may give support to seat designers and may enable a more complete assessment of aircraft seat.

2.1 Subjective Measures

Questionnaires and rating scales are used commonly in subjective evaluation to collect the feeling of potential passengers by the form of questions and scoring.

Rating scale methods are used for two types of (dis-)comfort assessment: general seated (dis-)comfort and local body discomfort. General (dis-)comfort rating allows potential passengers to express their overall well-being on the seat. Local discomfort ratings may permit identification of body areas that experience discomfort, the seat features and locations that cause bodily discomfort (Shen, 1994).

The well-known General Comfort Rating (GCR) scale was initially developed by Shackel et al. (1969) to measure general seating (dis-)comfort. Eleven statements were listed vertically along a 10 cm line with a short horizontal dash marked against each statement, running down the line according to the decreasing comfort level (see Figure 5). This GCR scale has been widely used for chairs and seats (dis-)comfort evaluation (Drury et al., 1982; Anderson and Helander, 1990; Bishu et al., 1988, 1991). With 11 points, the scale seemed to be very sensitive and could evaluate even small differences in comfort.



I feel completely relaxed.
I feel perfectly comfortable.
I feel quite comfortable.
I feel barely comfortable.
I feel uncomfortable.
I feel restless and fidgety.
I feel cramped.
I feel stiff.
I feel numb (on pins and needles).
I feel sore and tender.
I feel unbearable pain

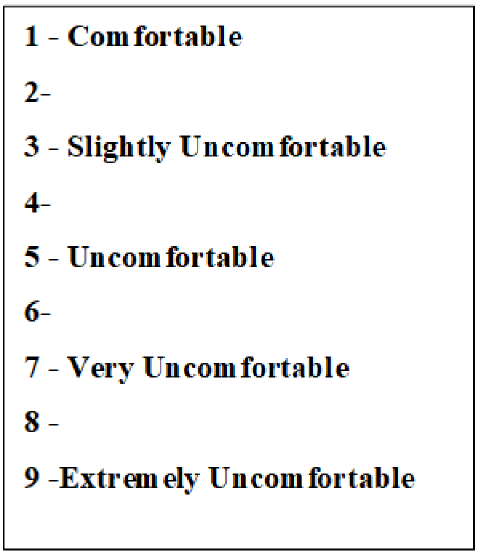
Figure 5. General Comfort Rating scale (Shackel et al., 1969)

Alternatively, uni-polar or bi-polar scales can be used to collect the perception of (dis-)comfort.

Bi-polar scales have two usually symmetrical ends, one for comfort and the other for discomfort. Corlett and Bishop (1976) used an overall comfort scale for the evaluation of working postures and this scale has often been used for seated comfort. Subjects were asked to indicate, on the 7-point bi-polar scale, the point which represented their current level of overall comfort. In the data processing stage, the scale points were halved and the scores allocated, for each subject, to the nearest half point. The left end of the scale was marked as *extremely comfortable* and the right as *extremely uncomfortable*. This scale has been widely used for evaluation of postural and seating discomfort (Kuorinka, 1983; Porter et al, 1992).

Uni-polar scales usually have only one dimension: the discomfort. Investigators who have used uni-polar scales for seated discomfort evaluation include: Eklund (1986), Yu et al. (1988), Bonney et al. (1990) and Beauchamp et al. (1990). In the evaluation of industrial seating, Eklund (1986) used a visual-analogue scale (VAS). Although there was no explanation about how the ratings were scored, the author stated that scale was sensitive in discriminating between different chair designs and also other design features. The reliability was judged as good, since the results agreed with other results obtained, such as spinal shrinkage measures. Yu et al. (1988) used an 8-point discomfort scale, anchored at two ends as 0-no discomfort and 7-extreme discomfort, to evaluate a work seat for industrial sewing operation. It seemed that the validity was good, and that the reliability could be indicated by the average coefficient of variation in ratings, which was 75%. However, the experiment used only 2 subjects.

Bonney et al. (1990) used another VAS to elicit subjective assessment of postural discomfort when postures involved flexion and/or rotation. Discomfort ratings were obtained at two-minute intervals over 10 minutes. Although no validation test was conducted for discomfort rating, the results showed that the adopted scale was valid for this purpose as well as reliable and sensitive to postural changes and to time. The scale used by Beauchamp et al. (1990) for assessing the effect of lateral tilting of seat on discomfort is presented in Figure 6. The first anchoring was *comfortable*, but it was equivalent to *no discomfort*. It should still be a discomfort scale rather than a bi-polar scale. The category definitions at each other point have followed the same dimension, that is discomfort. The ratings showed that the scale was valid and reliable as a linear regression model was well fitted to the average ratings and significant differences in discomfort were found between side tilt angles. Each 10 increase of tilting angle corresponded to one rating unit increase in discomfort.



1 - Comfortable

2-

3 - Slightly Uncomfortable

4-

5 - Uncomfortable

6-

7 - Very Uncomfortable

8 -

9 -Extremely Uncomfortable

Figure 6. Beauchamp 9-point discomfort scale

To identify special features and the locations of the seat areas that cause discomfort, body part discomfort (BPD) evaluation is more effective (Daley, 1985). The local discomfort ratings, if reliable, would correspond with ratings on general seated discomfort. Furthermore, BPD ratings are more closely related to psychophysical methods for stimulus-sensation studies than general discomfort. Widely accepted BPD scales are: ordinal discomfort scales, Corlett and Bishop BPD rating procedures and visual-analogue scales.

Ordinal scales for discomfort have anchoring phrases at each of the scale points, which are supposed to give users sufficient clues for rating. This type of scale is often used for field studies on vehicle seat discomfort (Babbs, 1979; Messenger and Griffin, 1990). The efficiency of these scales depends greatly on the structure of the scales, which includes the number of points to be used and the anchoring phrases. The most popular local discomfort scales are based on a procedure by Corlett and Bishop (1976), called BPD rating. During a study of the effects of posture on discomfort in spot welding, subjects were asked to indicate on a body map including 12 body areas (see Figure 7) the most uncomfortable body area(s), at 3/4 hour intervals throughout a 3 hour working period adopting a 6-point scale ranging from 0 (i.e. no discomfort) to 5 (i.e. extreme discomfort). The next most painful areas were then asked for and so on until no further areas were offered.

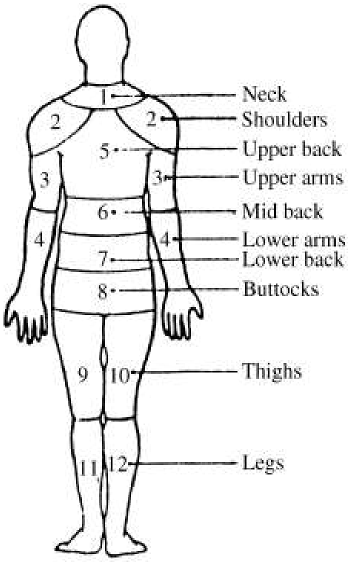
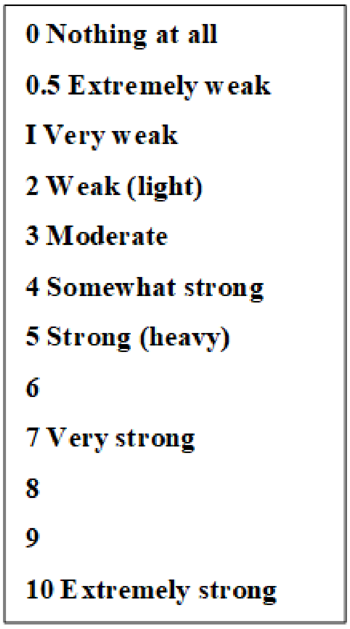


Figure 7. Body regions (Corlett - Bishop, 1976)

One of the attractive aspects of the BPD rating procedure is perhaps the body diagram with frequencies of reported discomfort. The BPD scale has been extensively used in chair and seat evaluations. There are different versions of the scale to accommodate relevant evaluations (Eklund and Corlett, 1986; Yu et al., 1988).

Finally, it is worth drawing attention to another type of scale adopted in the scientific literature to conclude our examination. Borg (1982) developed a 10-point category-ratio (CR-10) scale (Figure 8), dealing with intensity ratings in a wider psychophysical dimension. The CR-10 scale was reported to measure the stimulus intensity in an "absolute" way. The scale points range from 0 to 10 for simplicity. A "maximal" definition beyond 10 sets a subjective reference to avoid the ceiling effect. Other verbal anchors were placed on positions to shape a ratio scale.



0 Nothing at all

0.5 Extremely weak

I Very weak

2 Weak (light)

3 Moderate

4 Somewhat strong

5 Strong (heavy)

6

7 Very strong

8

9

10 Extremely strong

Figure 8. Borg's category-ratio (CR-10) intensity scale

2.2 Objective Measurement

The main objective measures used for seating comfort evaluation concern measurements of posture, number of body movements, estimations of muscle activation and muscle fatigue by electromyography (EMG), measurements of stature loss (spinal shrinkage), foot volume change and measurements of pressure distribution at backrest and seat pan (Shen, 1994). We will briefly introduce them, but particular attention during the research project was paid to the evaluation of pressure at the user-seat interface, because represents the less invasive and better correlated objective method with (dis-)comfort subjective measurements (De Looze at al., 2003).

Often the comfort evaluation is performed using the postures assumed by seat users. Seated posture is determined by the basic biomechanics of the spine, pelvis, thigh and the lower legs. When seated, a person maintains a rather upright trunk posture, while the body weight is supported by the seat.

The postural implications in seating predominantly involve the spine, whereas the supporting function of the seat is mainly fulfilled in the buttock and thigh areas. Biomechanical or physiological responses of seated persons may therefore provide objective measurements that can be related to the causes of seated discomfort.

Among the objective methods the joint angles correspond, with the pressure distribution, the widely used to carry out seat comfort assessments, especially in the field automotive. Joint angles can be defined as those angles that occur at the main articular joints of the human body. It has been shown that joint angles can be associated with seat comfort ratings (Lanzotti, 2008; Lanzotti et al., 2017). The seat must be designed to ensure correct posture, which can be assessed by measuring the joint angles. In the automotive field, ranges have been defined for the amplitudes of the main joint angles (Hanson et al., 2006; Kim et al., 1999; Porter and Gyi, 1998, Vogt et al.2005); in the aircraft sector, there is no such reference.

To examine the variety and intensity of seating postures under various seating conditions, postural angle analyses are developed (Dunk and Callaghan, 2005). One example is the *Ovako Working Posture Analysis System* which evaluates seating postures that are preferred in a real-world setting.

The system allows researchers to observe the frequency and duration in which each seating posture occurs and later evaluate its appropriateness to the task (Kroemer et al., 2001). This type of assessment is generally made thought the evaluation of the postural angles, obtained by photographic techniques or by opto-electronic systems, that are helpful for evaluation of the joint ranges of comfort (Babbs, 1979; Judic, 1993; Tilley, 1994). To evaluate postures and postural angles landmarks are sometimes used as in the study of Hiemstra-Van Mastrigt (2015) in which, at the start of the experiment, participants were equipped with stickers positioned on their head, shoulder, elbow, wrist (the palpable part of the posterior side of the semilunar bone), hip (greater trochanter), knee (lateral side of the patella) and ankle (lateral malleolus). After a fixed time, thanks to a picture made from the side, it was possible to evaluate the body angles, calculated by drawing lines between the stickers on top of the pictures.

Changes in the state and body movements (i.e. posture stability and mobility) seem to be the important factors especially for a long-term seating (Fenety, 2000; Vergara and Page, 2002) as can be for an air travel.

Some researchers showed that users start to move when they experience discomfort. During the stable condition the feeling of discomfort increases by a certain degree and when the discomfort reaches a certain level, the seating condition will shift to the unstable condition and discomfort will increase rapidly. When the discomfort further increases to reach a certain level, macro movement occurs and the feeling of discomfort will be reduced (Fujimaki and Noro, 2005).

Some studies measure the movement using the actigraphy that refers to accelerometers or motion-sensing devices (Telfer, 2009). Generally, this approach has been adopted during sleep studies to measure restlessness; in seating comfort research it has been used for measuring upper limb movement depending on the accelerometers incorporated in the actigraphy. Telfer (2009) used the actigraphy on 12 participants to assess discomfort in different chairs by measuring movement frequency.

Another objective measure is the motion analysis. Lijmbach (2014), who wanted to investigate the difference in experienced comfort by elderly and young passengers while using aircraft seat, used four cameras in order to study the human body movements during seating. The recording was analyzed with regard to different point such as number of hand contacts when sliding in the rows of seats and number of feet movements for ingress. Also the ELITE system used by Andreoni (2002) to evaluate car driver posture was equipped with four TV cameras.

Electromyography (EMG) system is always based on the assumption that a subject to reduce the seating discomfort makes movements giving rise to muscle activation. The estimations of muscle activation and muscle fatigue occurs throught EMG (Van Dieen, 2001; Ellegast, 2012). EMG is the study of muscle function through analysis of the electrical signals emanated during muscular contractions and can be used as a possible predictor for comfort index of a seat design (Lee, 1993). EMG cannot directly record subjective discomfort and, even for postural analysis, the results are often complex (Shen, 1994):

- seating and standing tasks normally require rather low muscle contraction. Typically, muscular activities in the trunk while seating are at or below 10% of their maximal capacities (Kroemer, 1991). Accordingly, the EMG values are small and easily interfered with by noise, such as electrical interference and electrode positioning problems. Therefore, the recorded data tend to have large errors relative to the actual level and analysis based on EMG data may not be reliable;
- EMG activity only reflects posture. It is sensitive to postural change so that principles could be derived about an appropriate range of postures that could be assumed in seating;
- there are no data about EMG thresholds for seated discomfort. Although the measurement procedures are well established, the criteria for assessment are highly variable (Kroemer, 1991). For example, while postural flexibility is desirable for prolonged seating, the EMG activity during postural change may be interpreted as a sign of excessive muscle activity, even though the absolute levels are very low.

An indicator of the loading on the spine is spinal shrinkage so it has been proposed to evaluate the discomfort of the back. Spinal shrinkage is the change in length of the spine under the influence of a change in compressive loading; it was estimated with a stadiometer (Van Dieen, 2001; Ellegast, 2012). Eklund and Coriett (1987) measured the stature loss (as a measure of spinal load) and they estimated the spinal forces on the basis of force measurements and posture recording. In their comparison between two seats it was found that the seat with the lowest stature shrinkage and lowest spinal force was always the seat with the least discomfort. Similarly, a tendency towards less general discomfort at less stature loss was found by Michel and Helander (1994), but only in a specific subgroup subjects namely 30 – 44 years old people with herniated discs.

Increased foot swelling seems to be associated with less local discomfort in the lower leg and feet. This result however was obtained by a study design where conditions represent different levels of allowed activity and not different seats (Winkel, 1986). This implies that it remains questionable whether foot volume change is a useful measure, providing the seat designers with valid information on the comfort or discomfort of different seats. Bendix et al. (1985), who also measured foot volume changes, did not find any variation in general comfort/discomfort across three office seats, hence they found no relationship with foot volume change (De Looze, 2003).

Finally, particular attention is paid to pressure distribution at the user-seat interface, that is the objective method most widely used in industry to carry out seating comfort evaluation.

Interface pressure is defined as the pressure distribution between the user and the seat. It has been extensively adopted to evaluate the occupant’s seating behaviors and perceived discomfort refers to office chairs or automotive seats.

Seating is a body position in which the body weight is transferred to a supporting area, mainly by the ischial tuberosities (IT, seating bones) of the pelvis and their surrounding soft tissues. Historically, measures of buttock and thigh compression have been used as a metric either assumed to be associated with seated discomfort or directly correlated with it based upon experimental subjective ratings of comfort or discomfort (Congleton et al., 1988; Ebe and Griffin, 2001; Gyi and Porter, 1999; Porter et al., 2003). Although past research has indicated a possible relationship between pressure and discomfort, recent studies suggested that any such relationship is neither simple, not direct and may exist only for certain population subsets (Gyi and Porter, 1999; Porter et al., 2003).

Automobile, truck, train, bus and aircraft manufacturers often use body pressure distribution measurements to assess discomfort. A review of Groenesteijn et al. (2009) allowed to identify 21 different studies that, between 1982 and 2000, have tried to establish reliable relationships between pressure measurements and evaluations of seating discomfort. For each study, the pressure measurement range, objective and subjective measures, protocol used, and the type of correlation with the perceived comfort detected at the end of the experiment are shown in Table 2.

Table 2. Groenesteijn et al., Review (2009)

Reference	**Objective measure for pressure**	**Subjective measure for comfort or discomfort**	**Study design (conditions, type of seats, number of subjects)**	**Conclusion on the relationship of the objective measure vs. (dis)comfort**
Lee et al. (1993)	Maximum and mean pressures, and gradients at the seat pan and back rest. (pressure sensitive mats)	General and local comfort/ discomfort (10-point scale)	Sixteen car seats with varying foam thickness and hardness, back contour, back and cushion angle, spring suspension rate and side support, N=100	No correlations were reported between pressure data and local comfort/discomfort 'Correlations not high enough for any design decisions', according to the authors
Thakurta et al. (1995)	Pressure distribution across various regions: shoulder, lumbar, ischial and thigh. (pressure sensitive mats)	Local comfort/discomfort (10-point scale	Five different cars (with different seats), N = 36	The authors conclude that pressure distribution correlates significantly with local comfort. However, no results are provided that illustrate these correlations
Yun et al. (1992)	The uniformity of the pressure distribution at upper, mid and low back and buttock area (pressure sensitive mat)	Local discomfort	Two different car seats, N = 18	The seat with the most even distributed pressure levels received the most favorable ratings for local discomfort. Pressure distribution significantly affects local discomfort particularly in the low back and buttock area
Kamijo et al. (1982)	Pressure distribution on the back rest and the seat pan (pressure sensitive mat)	General comfort/ discomfort (5-point scale)	43 car seats. General comfort was measured in 15 subjects, pressure distribution in 1 subject.	The comfort of a seat can be roughly determined on the basis of the pressure distribution at the backrest in height direction and the

				variance of pressure at the seat cushion along the body’s shape around both sciatic nodes
Vergara and Page (2000)	Time of contact between back rest and upper and low back (contact recording electrodes)	General comfort/discomfort (visual analogue scale) Local discomfort (10-point scale)	Six office seats varying in adjustability. One task including writing and reading, N = 6	More lumbar discomfort corresponds significantly to upper back contact only (thus, no low back contact) or no contact at all with the backrest
Tewari and Prasad (2000)	Mean pressure on the seat pan and back rest (pressure sensitive mats).	General comfort 6-point scale	Tractor seats varying in seat pan radius, back rest radius and back rest inclination, N= 3	Lower mean pressures on the seat pan correspond to a better and more comfortable seat profile

2.3 Passenger Comfort Surveys and Laboratory Experiments

Generally, the passenger (dis-)comfort experience is collected by passenger satisfaction survey. Advantages of this approach include the access to high number of passengers, even from different countries, the ability to reach participants difficult to contact and the convenience, in case of online survey, of having automated data collection, which reduces researcher time and effort. Disadvantages of survey research include uncertainty over the validity of the data and sampling issues, concerns surrounding the design, implementation and evaluation of the survey (Wright, 2005) and, moreover, the impossibility of combining subjective and objective measures of (dis-)comfort.

As an alternative to conducting large surveys, it is possible to design and conduct Laboratory experiments.

Laboratory experiments are recognized as a very effective strategy to collect suitable data for a diagnostic assessment of seating (dis-)comfort. The main advantages of laboratory experiments are: 1) researchers can control the environment under which potential passengers make their evaluations and they can also compare different seats and/or aircraft environments; 2) a small sample representative of the passenger target population can be considered; 3) it is possible to learn more about aircraft seat experience with a significant reduction in costs and time for data collection and analysis (Kremser et al., 2012; Vink, 2016); 4) participants reveal information about their "real time" comfort feelings (e.g. thermal comfort, noise, cabin comfort, seat comfort, legroom) rather than recall retrospective flight experiences as happens for surveys. Despite these advantages, experimenters are well aware that human responses in experimental research can be difficult to measure due to different critical points: 1) personal characteristics (e.g. demographic like age, nationality, income; physical like body size; physiological like blood pressure, state of health and general well-being; psychological linked to memory of previous flights, expectations about future experiences and personal preferences) make people experience different levels of (dis-)comfort in identical environments (e.g. Dunk and Callaghan, 2005; Kremser et al., 2012; Kyung and

Nussbaum, 2013; Bazley et al., 2015; Smulders et al., 2016; Vink, 2016; Molenbroek et al., 2017; Vanacore et al., 2019); 2) different personal experiences can cause people to react to the same situation in different ways and make it difficult to measure the human responses to different stimuli (i.e. experimental treatments); 3) individual differences in rating scale usage cannot be neglected; 4) the same participants generally test several items (e.g. physical products or concepts) and, of course, these evaluations cannot be assumed independent; 5) subjective comfort data are generally collected via ordered categorical scales, in which scores are meaningful only for comparison.

All these factors and their interdependencies cannot be neglected in order to end up with reliable and robust comfort analysis. Specifically, the first three criticisms may impact on the reproducibility and replicability of the study and they can be addressed by detailed experimental protocols and appropriate experimental design; the last two criticisms, instead, impact on the interpretation of comfort data and can be addressed by a suitable statistical modeling.

In Chapter 3 the attention is focused on the experimental design, whereas in Chapters 4 and 5 the suitable statistical models for (dis-)comfort data analysis and the main strategies for evaluating the pressure distribution data are analyzed.

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CHAPTER 3

This Chapter deals with the design of experiments and its benefits. The word *experiment* is used in a quite precise sense to mean an investigation where the system to be studied is under the control of the investigator. This means that the investigated individuals or material, the nature of the treatments and the used measurement procedures are all settled, at least in their important features, by the investigator (Cox and Reid, 2000).

Experiments imply that one or many input variables (experimental factors) are allowed to vary to affect the output (response(s)) with the aim of revealing potential causal relationships (effects) between factors and responses and providing estimates of these effects.

In a laboratory experiment, variables of interest are identified. One or more of these variables, referred to as the factors of the study, are controlled so that data may be obtained about how the factors influence another variable referred to as the response.

3.1 Design of Experiment

Design of experiments (DOE) is defined as a branch of applied statistics that deals with planning, conducting, analyzing and interpreting controlled tests to evaluate the factors that impact on the value of a parameter or a group of parameters.

It allows to manipulate multiple input factors determining their effect on a desired output (e.g. passenger comfort response). By manipulating multiple inputs at the same time, DOE can identify important interactions that may be missed when experimenting with one factor at a time.

Since the inferences that can be made depend on the way the experiment was carried out, the statistician should request a detailed description of the experiments and its objectives. For this reason, it is a good practice to make a written draft of the experiment proposal. Generally, this draft consists of three parts: 1) the statement of the objectives; 2) an experiment protocol with a description of the experiment; 3) an outline of method of analysis results (Cochran and Cox, 1992).

3.1.1 The statement of the objectives and the experimental protocol

This statement may be in the form of the questions to be answered, the hypothesis to be tested or the effects to be estimated. The aim should be to make the statement lucid and specific (Cochran and Cox, 1992). A good practice is to classify objectives as major and minor, which will make it easier to organize experimental activities and the roles of each member of the experimental team. It is obvious that worthwhile inferences about an extensive population cannot be made from a single experiment so the researcher has some population in mind to which she/he would like to apply the results. Thus, the statement should include an account of the area over which the generalization is to be made, in other words, of the population about which it is hoped to make inferences

The experimental protocol is a predefined procedural method in the design and implementation of an experiment; it is essential to guarantee the reliability and reproducibility of the collected data. Researchers keep detailed descriptions of their experiments in these documents (i.e. study objectives, reasoning for experimental design, reasoning for chosen sample sizes, safety precautions), instructions for the participants, equipment and measurement tools. For the experiment description it is enough to consider three important elements, namely the experimental units, the treatments and the response.

Experimental units are essentially the assessors, plots, raw material, etc. of the investigation. More formally they correspond to the smallest subdivision of the experimental material such that any two different experimental units might receive different treatments.

The treatments are clearly defined procedures, each applied to one experimental unit. In some cases, the treatments are an unstructured set of two or more qualitatively different procedures. In others, including many investigations in the physical sciences, the treatments are defined by the levels of one or more quantitative variables.

The response measurement specifies the criterion in terms of which the comparison of treatments is to be affected.

Generally, the aim is the comparison of the effects of treatments on response. This is typically assessed by estimates and confidence limits for the magnitude of treatment differences. Two essential requirements on such estimates are: firstly, to avoid systematic errors or biases; next, so far as feasible, the effect of random errors should be minimized.

The factors that cannot be controlled in a real environment (for example during a flight) but can be controlled in a research setting are deliberately varied as the so-called noise factors (Karazi et al., 2019). The definition of the control and noise factors, the choice of the response variable and the relevant treatments allow the definition of the most appropriate experimental plan to achieve the research objectives; it is fundamental for the definition of the test sequences. Then the experimental plan should be developed so as to provide meaningful information. At this step, it is essential to make sure that the relevant background information, like theoretical principles and knowledge obtained through observation or previous experimentation, has been studied. For instance, correct identification of which factors or process conditions affect process performance and contribute to process variability is necessary. Alternatively, if the process is already established and the influential factors have been identified, it may be required to determine the optimal process conditions. Factorial experiments, which make it possible to simultaneously calculate the effects of several factors and the treatment consist of all combinations that can be formed from the different factors, cost of a project, are the most common. In this chapter, we will focus on Latin and Graeco Latin Squares, moreover cross-over design will be introduced and discussed as a tool for collecting subjective data in laboratory environment. In conclusion, well-designed experiments can produce significantly more information and often require fewer runs than random or unplanned experiments. Furthermore, a well-designed experiment ensures the assessment of the effects identified as important. For instance, if there is an interaction between two input variables (i.e. the effect of one input variable is affected by the level of another input variable; Antony, 2014; Cochran and Cox, 1992; Eriksson, 2008), both variables should be considered in the design rather than doing a “one factor at a time” experiment.

3.2 Cross-over Design

One of the key assumptions underlying all the previous discussion is that the response on any unit depends on the treatment applied to that unit independently of the allocation of treatments to the other units. However, when the same individual (or physical object) is used as an experimental unit several times, the assumption needs more critical attention and may indeed be violated.

Crossover designs are a mixture of within- and between-groups designs (Krauth, 2000); it is a design where each experimental unit (e.g. potential passenger) receives a series of treatments over time. That is, they can be used to compare treatments to one another where each treatment is administered to the same experimental unit (such as a potential passenger). Each experimental unit receives each treatment in a predetermined sequence. The time points at which the various treatments are assigned are usually called periods.

In a crossover design, each experimental unit serves as its own control. Thus, a crossover design should give smaller standard errors for comparisons between treatments than a design where treatments are assigned to different subjects (called a parallel subjects design). While crossover designs should reduce the standard errors for treatment comparisons, a problem may occur if there are carryover effects or residual effects from a treatment given in one period to a treatment given in a subsequent period.

In the general crossover design, t treatments observed on as many different experimental units are compared, i.e., the treatments are applied in a predetermined sequence to an experimental unit. There are s sequences of the t treatments and the available experimental units are randomly assigned to the s sequences (Johnson, 2010). The sequences to be assigned to the experimental units are defined according to appropriate experimental plans that depend on the number of treatments to be administered and the number of noise factors to be controlled. A quite common application of cross over design is in clinical trials of drugs. In its simplest form there are two treatments, say T and C; some patients receive the drug T in the first period and C in the second period, whereas other patients have the order C- T. These two treatment/two period designs can be generalized in various obvious ways by extending either the number of treatments or the number of periods or both of them.

Any effect on one experimental unit arising from treatments applied to another unit is called carry-over or residual effect. It is unlikely, although not impossible, that the carry-over of a treatment effect from one period to another is of intrinsic interest. Two important crucial points are that even in the absence of carry-over effects it is possible that treatment effects estimated in an environment of change are not the same as those in a more stable context (Cox and Reid, 2000). The second point is that it will often be possible to eliminate, or at least substantially reduce, carry-over effects by wash-out periods restoring the material so far as feasible to its initial state.

Looking at the simplest cross-over design in detail, we regard two periods asymmetrically, supposing that all individuals start the first period in the same state whereas it is manifestly not true for the second period.

In the first period let the treatment parameter be $\pm\delta$ depending on whether T or C is used and in the second period let the corresponding parameter be $+(\delta+\gamma)$, measuring a treatment by period interaction. Next suppose that in the second period a carryover or residual effect of $\pm\rho$ is added to the treatment effect following T or C, respectively, in the first period. Finally let π denote a systematic difference between observations in the two periods.

For individuals receiving treatments in the order C-T, the expected value of the first and second observations are, omitting individual unit effects:

$$\mu-\delta,\ \ \mu+\delta+\gamma-\rho+\pi \tag{3.6}$$

whereas for the complementary sequence the values are:

$$\mu+\delta,\ \ \mu-\delta-\gamma+\rho+\pi \tag{3.7}$$

Thus, the mean of the differences within individuals estimates are respectively:

$$2\delta+\pi+\gamma-\rho,\ \ -2\delta+\pi-\gamma+\rho \tag{3.8}$$

and the difference of these estimates leads to the estimation of:

$$2\Delta + 2(\gamma - \rho)$$

where $\Delta = 2\delta$. In addition, assuming that the first period treatment effect Δ is a suitable target parameter, it can be estimated from the first period observations alone, but only with low precision because the error includes a between individual component. If this component of variance were small there would be little advantage to the cross-over design anyway.

This analysis confirms the general conclusion that the design is suitable only when there are strong subject-matter arguments for supposing that any carry-over effect or treatment by period interaction are small and that there are substantial systematic variations between subjects.

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CHAPTER 4

In this chapter the most proper statistical models for the analysis of the subjective (dis-)comfort data will be analyzed; as shown in Chapter 2, these data are generally collected using ordinal scales.

Ordinal measurements as ratings, preference and evaluation data are very common in (dis-)comfort research studies; the statistical analysis of ordinal data requires a proper modelling approach for interpretation, classification and prediction of response patterns. In the literature, the evaluation of subjective data is generally carried out using classical analysis techniques (i.e. ANOVA, linear regression, etc.) that are not always adapted to the specific nature of the data.

Ordinal data arise when qualitative categories are given an ordered restraint; so, they are generated by grouping continuous measurements or by genuine ordinal outcomes (Anderson, 1984; Anderson & Philips, 1981). We will consider ordinal data in the special case they stem from sample surveys where interviewees are asked to express opinions, judgements, evaluations, preferences, etc. by means of a list of verbal ratings (as ‘very unsatisfied’, ‘unsatisfied’, ‘indifferent’, ‘satisfied’ and ‘very satisfied’) or scores, for example as integers from 1 to 7 or from 0 to 10 (Piccolo et al., 2019).

As in all statistical analyses dealing with subjective judgments or evaluations, it is complicated to highlight systematic elements and influencing factors. First, because it is necessary to isolate a component of uncertainty in the data represented by hastily quantified evaluations or evaluations moved by contingent states of mind. It is necessary, therefore, to identify models capable of capturing this complexity of data and highlighting the truly relevant components.

Current approaches for analyzing rating data are based on generalized linear models (GLMs) and their extensions (McCullagh, 1980; McCullagh & Nelder, 1989).

In this scenario, a different paradigm has been introduced consisting in CUB models (Piccolo, 2003) a convex combination of two discrete probability distributions in their basic formulation.

The first aim of this chapter is to provide proper statistical models for (dis-)comfort data analysis in order to determine if there is any significant effect of selected factors (e.g. seat features, passengers characteristics, etc.) on the subjective (dis-)comfort perception experienced by the potential passenger during experiments in controlled environments (e.g. laboratory or fuselage). From a methodological point of view, two different models able to explain the subjective evaluation of comfort are adapted. For each model, the causes that let it be considered a priori plausible to explain the seat comfort under study will be identified, analyzing the components and peculiarities.

Responding to the need to provide more reliable tools for the analysis with more robust statistical evidence (Hiemstra-van Mastrigt et al., 2017), the introduction of these statistical models for assessing the comfort experience represents a breakthrough for the specialized literature, which generally adopts approaches based on hypothesis tests, without taking into account the specific nature of ordinal data; moreover, a proper data analysis via statistical models also allows to make predictions and provides diagnostic tools to improve the seat, even at the design stage.

4.1 Generalized Linear Models

In this paragraph a family of generalized linear models (GLMs) that contains the most popular models for categorical responses as well as standard models for continuous responses will be introduced.

GLMs extend ordinary regression models to encompass non-normal response distributions and modeling functions of the mean. Three components specify a generalized linear model: a random component identifies the response variable (hereafter denoted as R) and its probability distribution; a systematic component specifies explanatory variables used in a linear predictor function and a link function specifies the function of $E(R)$ that the model equates the systematic component. Nelder and Wedderburn (1972) introduced the class of GLMs, although many models in the class were well established by then (Agresti, 2003).

4.1.1 Components of generalized linear models

The random component of a GLM consists of a response variable R with independent N observations $(r_1,..., r_N)$ from a distribution in the natural exponential family. This family has probability density function or mass function given by:

$$f\left(r_i;\theta_i\right)=a\left(\theta_i\right)b\left(r_i\right)\exp\left[r_iQ\left(\theta_i\right)\right] \tag{4.1}$$

Several important distributions are special cases, including the Poisson and Binomial. The value of the parameter θ_i may vary for i=1,..,N. The term $Q(\theta)$ is called the natural parameter.

The systematic component of a GLM relates a vector ($\eta_1,\ldots,\eta_N$) to the explanatory variables through a linear model. Let x_{ij} denote the value of predictor j (j = 1, …, p) for subject i. Then

$$\eta_i=\sum_j \beta_j x_{ij}, \qquad i=1,\ldots,N \tag{4.2}$$

This linear combination of explanatory variables is called the linear predictor. The third component of a GLM is a link function that connects the random and systematic components. Let $\mu_i = E(R_i)$, i = 1…, N. The model links μ_i to η_i by η_i = g(μ_i), where the link function g is a monotonic, differentiable function. Thus, g links $E(Y_i)$ to explanatory variables through the formula:

$$g(\mu_i)=\sum_j \beta_j x_{ij}, \qquad i=1,..,N \tag{4.3}$$

The link function η_i = g(μ_i) is called the identity link and it has $\eta_i = \mu_i$. It specifies a linear model for the mean itself. This is the link function for ordinary regression with normally distributed R. Multicategory responses use multinomial GLMs so that we generalize logistic regression for multinomial ordinal response variables. In summary, a GLM is a linear model for a transformed mean of a response variable that has distribution in the natural exponential family.

4.1.2 Cumulative Logit Model (CLM)

Models with terms that reflect ordinal characteristics such as monotone trend have improved model parsimony and power. In this section the most popular logit model for ordinal responses is introduced, that is the Cumulative Logit Model (CLM).

When response categories are ordered, the logits can utilize the ordering. A cumulative probability for R is the probability hat R falls at or below a particular point. For outcome category j, the cumulative probability is:

$$P\left(R \le j\right) = \pi_1 + \pi_2 + \ldots + \pi_j, \quad j = 1,..,m$$

The cumulative probabilities reflect the ordering, with:

$P\left(R \le 1\right) \le P\left(R \le 2\right) \le P\left(R \le 3\right) \le \ldots \le P\left(R \le j\right) = 1$ (Agresti, 2018).

The cumulative logits are defined as:

$$\log it\left[P\left(R \le j \middle| \mathbf{x}\right)\right] = \log \frac{P\left(R \le j \middle| \mathbf{x}\right)}{1 - P\left(R \le j \middle| \mathbf{x}\right)} = \log \frac{\pi_1\left(x\right) + \ldots + \pi_j\left(x\right)}{\pi_{j+1}\left(x\right) + \ldots + \pi_J\left(x\right)} \quad j = 1,\ldots,m\text{-}1 \tag{4.4}$$

Each cumulative logit uses all *m* response categories. A model for logit $P\left(R \le j\right)$ alone is an ordinary logit model for a binary response in which categories from 1 to *j* form one outcome and categories from *j+1* to *m* form the second outcome. Better, models can use all *m–1* cumulative logits in a single parsimonious model.

A model that simultaneously uses all cumulative logits is:

$$\log it\left[P\left(R \le j \middle| \mathbf{x}\right)\right] = \alpha_j + \boldsymbol{\beta}'\mathbf{x} \quad j = 1,\ldots,m\text{-}1 \tag{4.5}$$

Each cumulative logit has its own intercept. The $\{\alpha_j\}$ are increasing in *j*, since $P\left(R \le j \middle| \mathbf{x}\right)$ increases in *j* for fixed x, and the logit is an increasing function of this probability. This model has the same effects **β** for each logit (Agresti, 2003).

The cumulative logit model (4.5) satisfies the following condition:

$$\begin{aligned} &\log it\left[P\left(R \le j \middle| \mathbf{x}_1\right)\right] - \log it\left[P\left(R \le j \middle| \mathbf{x}_2\right)\right] = \\ &= \log \frac{P\left(R \le j \middle| \mathbf{x}_1\right) / P\left(R > j \middle| \mathbf{x}_1\right)}{P\left(R \le j \middle| \mathbf{x}_2\right) / P\left(R > j \middle| \mathbf{x}_2\right)} = \boldsymbol{\beta}'\left(\mathbf{x}_1 - \mathbf{x}_2\right) \quad j = 1,\ldots,J\text{ -}1 \end{aligned} \tag{4.6}$$

An odds ratio of cumulative probabilities is called a cumulative odds ratio. The log cumulative odds ratio is proportional to the distance between $\mathbf{x}_1$ and $\mathbf{x}_2$. The same proportionality constant applies to each logit. Because of this property, McCullagh (1980) called the model (4.5) “proportional odds model”.

4.1.3 Parameter Estimation

Model (4.4) constrains the *m-1* response curves to have the same shape. Thus, its fit is not the same as fitting separate logit models for each category *j*. Again let ($y_{i1},\dots,y_{im}$) be binary indicators of the response for subject *i*. The likelihood function is:

$$\prod_{i=1}^{N}\left[\prod_{j=1}^{m}\pi_j(\mathbf{x_i})^{r_{ij}}\right]=\prod_{i=1}^{N}\left[\prod_{j=1}^{J}\Big(P\big(R\le j\,|\,\mathbf{x}_i\big)-P\big(R\le j-1\,|\,\mathbf{x}_i\big)\Big)^{r_{ij}}\right]=$$
$$=\prod_{i=1}^{N}\left[\prod_{j=1}^{m}\left(\frac{\exp(\alpha_j+\boldsymbol{\beta}'\mathbf{x_i})}{1+\exp(\alpha_j+\boldsymbol{\beta}'\mathbf{x_i})}-\frac{\exp(\alpha_{j-1}+\boldsymbol{\beta}'\mathbf{x_i})}{1+\exp(\alpha_{j-1}+\boldsymbol{\beta}'\mathbf{x_i})}\right)^{r_{ij}}\right] \tag{4.7}$$

viewed as a function of ($\{\alpha_j\}$, $\boldsymbol{\beta}$). McCullagh (1980) and Walker and Duncan (1967) used Fisher scoring algorithms to obtain ML estimates. The significance of parameters and the global validation of the estimated model are performed according to asymptotic likelihood-based and descriptive measures (Veall & Zimmermann, 1996). Thus, deviance and Pearson statistics are frequent – as in Agresti (2010) and Tutz (2012) – as well as generalized residuals, introduced by Pregibon (1981) and successfully applied for dichotomous and ordered polytomous data analysis. Their introduction has been mainly suggested for checking the presence of outliers and the validation of the model, as in Franses and Paap (2001), or for defining pseudo-R^2-type measures, as for example in Hűbler (1977) and Veall & Zimmermann (1996).

4.2 Generalized Linear Mixed Models: Cumulative Link Mixed Model (CLMM)

In comfort analysis the observations generally occur in clusters. For instance, cluster *i* might consist of repeated measurements on subject *i* or observations for all subjects in family *i*. Observations within a cluster tend to be more alike than observations from different clusters. Thus, they are usually positively correlated. Ordinary analyses that ignore the correlation and treat within-cluster observations the same as between-cluster observations produce invalid standard errors (Agresti, 2003).

Recently random effects models have been used much in models for categorical data. In this paragraph generalized linear models will be extended to include random effects leading to the so called generalized linear mixed model (Agresti and Caffo, 2000). Specifically, the attention will be focused only on cumulative logit mixed model (CLMM), that is an extension of CLM where random effects are included in the location part of the predictor. It can also be viewed as an extension of linear mixed models to ordered categorical observations. This framework is more flexible than the quasi-likelihood approach and allows for a more insightful modeling of grouping structures. Cumulative link mixed models is a member of a class of models sometimes referred to as multivariate generalized nonlinear mixed models (Fahrmeir and Tutz, 2001). The latent variable interpretation carries over to the mixed versions of cumulative logit models (Christensen et al., 2013). The CLMM relies on the idea that a subjective evaluation expressed on an ordinal scale (e.g. comfort rating) is actually a categorized version of an unobservable (latent) continuous variable. Let Y_i be the outcome category selected by subject i for the response variable. Given a set of p covariates, $(x_1 ,.., x_p)$ the CLMM can be formulated as follows (Agresti, 2010):

$$\operatorname{logit}\left[P\left(R \le j \mid \mathbf{x}_\mathbf{i}, \mathbf{u}_\mathbf{i}\right)\right] = \alpha_j + \mathrm{u}_i + \boldsymbol{\beta}'\mathbf{x} \quad j = 1,...,m\text{-}1 \tag{4.8}$$

where the parameter $\boldsymbol{\beta}$ measures the impact of $\mathbf{x}$ on R; the parameters α_j are the category cut-points on a standardized version of the latent variable and u_i is the random effect due to subject i for response categories $j = 1, 2, . . . , m\text{-}1$, assumed normally distributed and centered at zero ($\mathrm{u}_i \sim N(0, \sigma_u^2)$).

When a random effect is included in the model, it is important to look at the intra-class correlation. The Intra-class Correlation (ICC) is defined as the correlation of observations within a group and it is a way to look at how similar these within cluster observations are to one another. ICC is calculated as follow:

$$ICC = \frac{\hat{\sigma}_u^2}{\hat{\sigma}_u^2 + \sigma^2} \tag{4.9}$$

where $\hat{\sigma}_u^2$ represents the estimated variance of the random effect and σ^2 is the residual variance; assuming an underlying standard logistic latent variable, ICC can be calculated as $\sigma^2 = \pi^2/3$. Values of ICC near 1 indicate that observations within a cluster are very similar to one another; whereas values of ICC close to 0 indicate that the random effect can be neglected since observations within a group are nearly independent (Agresti, 2010; Christensen and Brockhoff, 2013).

The model-fitting process estimates the fixed effects and the standard deviation $\hat{\sigma}_u$ of the random effects.

4.2.1 CLMM Parameters Estimation

The model-fitting process estimates the fixed effects and the standard deviation of the random effects that describes the variability among clusters. Hedeker and Gibbons (1997; 2006), Tutz and Hennevogl (1996), and Hartzel et al. (2001) discussed model fitting for ordinal random effects models. An ordinal mixed model can be regarded as a two-stage model. At the first stage, conditional on the random and fixed effects, observations are assumed to be independent, as in an ordinary multinomial model. At the second stage, the random effects are assumed to be independent realizations from a normal distribution. Integrating out the random effects gives a marginal distribution for the response outcomes and a marginal likelihood function. This is a function of the fixed effects parameters and the parameter of the N (0, σ_u^2) random effects distribution. Averaged with respect to the distribution of the $\{u_i\}$, the model implies non-negative correlation among observations within a cluster. For each of the T_i observations in cluster i, let the response y_{it} for observation t be represented by a vector of binary indicators.

That is, let $y_{ijt} = 1$ if the observation falls in category j and let $y_{ijt} = 0$ otherwise, $i = 1, ..., n$; $j = 1, ..., m$; $t = 1, ..., T_i$.

Given u_i, let $\pi_j(x_{it}; u_i) = P(y_{ijt} = 1)$, then y_{it} can be assumed as a multinomial observation with probability mass function given by:

$$\pi_1(x_{it}; u_i)^{r_{i1t}} \pi_2(x_{it}; u_i)^{r_{i2t}} \pi_3(x_{it}; u_i)^{r_{i3t}} ... \pi_c(x_{it}; u_i)^{r_{ict}}$$

Each term in this product is a difference of cumulative probabilities with the inverse link function:

$$\pi_j\left(x_{it};u_i\right)^{r_{ijt}} = h^{-1}\left(u_i+\alpha_j+\mathbf{x}_{\mathbf{it}}^{'}\boldsymbol{\beta}\right)-h^{-1}\left(u_i+\alpha_{j-1}+\mathbf{x}_{\mathbf{it}}^{'}\boldsymbol{\beta}\right)$$

If u_i follows N (0, σ_u^2) probability density function, the marginal likelihood function has the form:

$$\prod_{i=1}^{n}\left\{\int_{-\infty}^{+\infty}\left[\prod_{t=1}^{T_i}\prod_{j=1}^{m}\left(h^{-1}\left(u_i+\alpha_j+\mathbf{x}_{\mathbf{it}}^{'}\boldsymbol{\beta}\right)-h^{-1}\left(u_i+\alpha_j+\mathbf{x}_{\mathbf{it}}^{'}\boldsymbol{\beta}\right)\right)^{r_{ijt}}\right]\left(\frac{1}{\sqrt{2\pi}\sigma_u}e^{-u_i^2/2\sigma_u^2}\right)du_i\right\} \tag{4.10}$$

The main computational difficulty in fitting CLMM is the need to evaluate this integral to obtain the marginal likelihood function. The integral does not have a closed form. Numerical methods for approximating the marginal likelihood function can be computationally intensive, especially for models with multiple random effect terms. Once the marginal likelihood function is approximated, standard methods such as the Newton-Raphson algorithm can maximize it, yielding ML estimates of parameters. As a by-product, inverting the approximated observed information matrix provides a large-sample covariance matrix for ML estimates. Inference about fixed effects then proceeds in the usual way (Agresti, 2010).

For relatively simple CLMM such as random intercept models, Gauss-Hermite quadrature approximates the integral that determines the marginal likelihood function by a finite weighted sum that is evaluated at certain quadrature points. Essentially, the normal density is approximated by a discrete histogram with bars centered at the quadrature points. The approximation improves as the number *q* of quadrature points increases. Similarly, as *q* increases, subsequent approximations for the ML parameter estimates and their SE values improve. Monte Carlo methods simulate the parameters to approximate the integral that determines the marginal likelihood function. The Gauss-Hermite and Monte Carlo methods approximate the ML parameter estimates but converge to the ML estimates as they are applied more finely: for example, as the number of quadrature points increases for numerical integration. This is preferable to other approximate methods that are simpler but need not yield estimates near the ML estimates. Such approaches, such as Laplace approximation and penalized quasi likelihood (PQL), replace the function to be integrated by an approximation for which the integral has closed form (e.g., Keen and Engel, 1997;

Hartzel et al., 2001). Another approach to model fitting is Bayesian according to which the distinction between fixed and random effects no longer occurs; a prior distribution is assumed for each effect of either type (Agresti, 2010).

4.3 Combination of Uniform and Binomial Model (CUB)

The statistical Combination of Uniform and Binomial model, CUB (Piccolo, 2003; Iannario, 2007; Tutz et al., 2014), as suggested by its name, is based on the joint use of two different distributions: the Uniform distribution and the Binomial distribution. The model works with ordinal response variables that usually represent a quantitative evaluation expressed about a given item (D' Elia and Piccolo, 2005; Oberski and Vermunt, 2015), for example the overall comfort of specific seat.

Formally, it is directly modelled the probability that a random variable R takes on discrete values $1,....m$, with m categories of the response variable. The basic idea underlying this model is that, when an individual is asked to express his/her evaluation on a scale of discrete ordered alternatives, the psychological mechanism leading to the choice is influenced by both a rational reasoning component and a general uncertainty in choosing the response category. These two components, one referred to as rational reasoning (*feeling*) and the other as uncertainty of the decision-making process (*uncertainty*), are separately modeled with the shifted Binomial and Uniform distributions, respectively.

In detail, two different random variables are considered: the former distributed as a shifted Binomial and the latter as a Uniform. The shifted Binomial distribution represents an attempt to discretize the latent judgment process and, therefore, it is proposed to assign to an unobserved evaluation of continuous character a mode among a set of discrete values $1, ..., m$. Through this random variable, the aim is to explain the rational component leading to the choice of response category and observe, with the inclusion of specific covariates, whether there is evidence of significant factors contributing to the determination of the response variable. The Uniform distribution, which foresees a constant probability level for each element of the support, is instead suitable to describe the uncertainty inherent in a decision process that requires to identify a discrete mode of response and represents the model with the highest degree of entropy on a discrete support. Through this aleatory variable it is attempted to explain and control the general confusion in the response process that pollutes rational reasoning by blurring it.

The psychological mechanism that leads the individual to indicate the category of the response variable is, therefore, the result of the combination of two behaviors that could be defined as extreme: the choice motivated solely by reasoning and the decision generated solely by chance.

What is practically done in the CUB model is to consider the response as a combination of these two elements and, therefore, to express the observed response mode *r* as the realization of a random variable *R* defined as a mixture of a Uniform and a shifted Binomial.

The probability mass function is as follows:

$$\Pr\left(R=r\middle|\pi,\xi\right)=\pi\binom{m-1}{r-1}\xi^{m-j}\left(1-\xi\right)^{j-1}+\left(1-\pi\right)\frac{1}{m} \qquad (4.11)$$

with $\pi \in [0,1]$, $\xi \in [0,1]$. The parameter π is inversely linked with the uncertainty, the more relevant is the estimated value of π, the less important the uncertainty component is in the model. In other words, the factor $\frac{(1-\pi)}{m}$, portion of constant probability distributed on the support, can be seen like a species of uncertainty share that gives direct information about the weight assumed from the component of the uncertainty in the general model.

The parameter ξ, whereas, is directly related to the feeling component that leads to the identification of the response category and explicitly represents in case the ordinal scale is ordered from *m* to 1 (with 1 being the most positive value), a measure of the strength of the feeling component. However,it should be noted that in case the ordering of the response categories is arranged from 1 to *m* (with *m-th* category indicating the best rating), the interpretation of ξ is reversed and the comment in terms of $(1 - \xi)$ is deemed more convenient. Thus, in the case of working with a response variable whose modes are ordered in an increasing sense, the 1's complements of the parameters π and ξ are the direct measures of feeling and uncertainty. The impact of ξ and π on the response variable is not easy to infer, since it is a mixture model and the two components interact.

In order to interpret the parameters, the impact on the response variable generated by changing the value assumed by one of the two parameters while keeping the value of the other fixed is observed. In other words, it is observed, for given values of ξ, how the probability of indicating each response category changes as π changes. And, in parallel, it is investigated, for given values of π, how the probability of indicating each response category changes as ξ changes. As an example, consider a 3-category response variable ordered in an ascending sense, although the analyses and conclusions could be generalized to situations in which the response variable involves more than 3 modes. Let ξ vary over its domain and observe the variation of the probability of each response category; for fixed values of the parameter π, different probabilities for each of the three response categories are observed as ξ varies.

Regardless of the value of π, the curves related to the probabilities of responding the extreme categories, i.e. the first and third, present a decreasing and increasing monotonic trend, respectively. In contrast, the curve related to the middle category will have a bell-shaped trend. Specifically, observing the trend of the curves for segments of the ξ domain regardless of the value of π, 3 scenarios emerge:

- for $\xi<0.5$, the probability of responding with the highest category of the response variable is highest at $\xi=0$ and progressively decreases until it reaches its minimum at $\xi=0.5$. In contrast, the probabilities of the first and second categories have minimum value at $\xi=0$ and progressively increase until $\xi=0.5$;

- for $\xi=0.5$, the probability of responding with the central category of the response variable reaches a maximum and the probabilities of belonging to the two extreme categories, the first and the third, are equivalent;

- for $\xi>0.5$, the probability of answering the minimum category of the response variable is maximum at $\xi=1$ while the probability of answering the central category, past the value $\xi=0.5$, gradually decreases until it reaches its minimum at $\xi=1$.

This occurs for each value of π. Thus, the change in the value assumed by this parameter does not affect the structure described above, but it does affect the distance between the probabilities of the three response categories.

Similarly, the parameter π is varied over its domain and the variation of the probability of each response category observed.

Regardless of the value of ξ at $\pi = 0$, all categories have the same probability: the component related to the Binomial shifted in the CUB model elides and only the component of the Uniform random variable persists to fully determine the response. Second, we note that, in any case, the curves still retain a monotonic and, essentially, linear trend.

But, compared to the previous case, varying the fixed parameter ξ substantially affects the response variable as the parameter π changes so that:

-for $\xi<0.5$, as π increases, the probability of responding the maximum category of the response variable increases and, conversely, the probability of the first category decreases. The probability of answering the middle category remains essentially stable on the initial value;

- for $\xi=0.5$, the response probabilities of the two extreme categories are equal while the increase of π generates the increase of the response probability of the central category reaching the maximum value at $\pi=1$;

- for $\xi>0.5$, a mirror situation of the first described, as π increases, the probability of answering the minimum category of the response variable increases and, conversely, the probability of the maximum category decreases. The probability of answering the central category remains essentially stable on the initial value.

The CUB model is based on the joint analysis of the components of feeling and uncertainty in an attempt to explain, through these two elements, the response variable. The interesting aspect is the analysis of how candidate covariates influence each of the two components that is which characteristics of the respondents or of the object of analysis can alter the propensity to respond greater or lesser categories of the response variable. This alteration can occur either directly, through a decisive influence of the feeling component, or indirectly by affecting the tendency to follow logical reflection only marginally, letting oneself be carried away by external agents and even by chance.

Introducing covariates, i.e. assuming that the feeling and uncertainty parameters are influenced by subject-specific characteristics, the model can be redefined by considering the probability that the i-th subject will respond to response category *j* as a function also of its covariates. It can be chosen whether to include covariates only in support of uncertainty, feeling or both. In the case of including *p* covariates in the uncertainty explanation and *q* in support of the feeling, the so-called stochastic component of the CUB (*p*,*q*) model can be expressed as follows:

$$\Pr\left(R_i = r \middle| \boldsymbol{\beta}, \boldsymbol{\gamma}\right) = \pi_i \binom{m-1}{r-1} \xi_i^{m-r} \left(1-\xi_i\right)^{r-1} + \left(1-\pi_i\right)\frac{1}{m} \tag{4.12}$$

where $\boldsymbol{\beta}=\left(\beta_0,\dots,\beta_p\right)$ is the parameter vector of covariates related to the uncertainty component and $\boldsymbol{\gamma}=\left(\gamma_0,\dots,\gamma_q\right)$ is the parameter vector of covariates related to the feeling component.

Assuming, as in most cases, that between the covariates and the parameters the link of feeling and uncertainty is logit, two systematic components of the model can be defined as follows:

$$\pi_i = \frac{1}{1+\exp(-y_i\beta)} \tag{4.13}$$

$$\xi_i = \frac{1}{1+\exp(-w_i\gamma)} \tag{4.14}$$

It is worth to note that there is a direct link between π_i and ξ_i and the parameter vectors related to the covariates, respectively y_i and w_i.

After the investigation of the influence of π and ξ on the response variable, and thus on the probability of the different response categories, it is necessary, at this point, to focus on the influence of the covariates. This analysis is decisive in the correct interpretation of the parameters and of the role that the explanatory factors play in the overall model.

The effects of covariates significant for the feeling component are easier to understand than those significant for the uncertainty parameter. In case the parameter estimate for a variable is positive, the increase in the explanatory variable causes a positive change in ξ_i which, in turn, leads to a leftward shift in the probability function of choice of the ordered categories and, consequently, a tendency to respond to the lower categories. Conversely, if the parameter estimate is negative, the increase in the mode assumed by the variable corresponds to a decrease in ξ_i which causes the effect of pushing the subject towards the higher response categories.

The effect of significant covariates for the uncertainty component, however, is more complex, as it is inextricably linked to the feeling component. Generally, it can be said that the positive sign of a parameter estimate of a covariate related to uncertainty causes an increase in the value of π_i and, therefore, a lower significance of the uncertainty component (defined as $1 - \pi_i$). Conversely, it happens with a negative estimated value of the parameter. But the influence on the response variable is not easy to predict as it is confused in the feeling. What can be said, however, is that a positive value of a parameter related to a variable significant for uncertainty, generates an increase in the value of π_i and, consequently, increases the relevance of feeling in the decision-making process, thus emphasizing the trends that are already manifest in the rational component. Vice versa, a negative value of the parameter indicates that the variable to which this parameter is linked has the effect of reducing trends, increasing uncertainty.

4.3.1 CUB Parameters Estimation

The parameters are estimated via the maximum likelihood method (Iannario and Piccolo, 2010; Piccolo and Simone, 2019). In this regard, the elements j_i, y_i , w_i, respectively the responses of each *i*-th subject (of the total *N*) and the values assumed by the covariates are considered and the log-likelihood function of the model with vector of the parameters $\boldsymbol{\theta}=(\boldsymbol{\beta},\boldsymbol{\gamma})$ is:

$$l(\boldsymbol{\theta})=\sum_{i=1}^{N}\log\left\{\frac{1}{1+e^{-y_i\boldsymbol{\beta}}}\left[\binom{m-1}{j_i-1}\frac{e^{(-w_i\boldsymbol{\gamma})(j_i-1)}}{\left(1+e^{(-w_i\boldsymbol{\gamma})}\right)^{m-1}}-\frac{1}{m}\right]+\frac{1}{m}\right\} \tag{4.15}$$

Parameter estimation is done through the Estimation and Maximization algorithm (EM). To verify the significance of the parameters it is possible to compare the log-likelihood of the model in question with the log-likelihood of the saturated model or with that of the null model.

In alternative, one can focus on the uncertainty or feeling parameters by comparing the CUB (p,q) model with a CUB (0,q) (to test the impact of covariates related to uncertainty) or CUB (p,q) with a CUB (0,q) model (to test the impact of covariates related to uncertainty) or CUB (p,0) (to test the impact of covariates related to feeling). Finally, to measure the global goodness of fit, it is possible to use various indices for example BIC index or Dissimilarity Index.

4.3.2 CUB model with object covariates

Objective information relates to covariates which are functions of items and specify both quantitative and qualitative aspects (related to content, appearance, structure, texture, ingredients, etc.). Objects' covariates are denoted by **x**. Specifically, for each object $j = 1, 2, \ldots, J$, the H covariates characterizing the *j*-th object are denoted as $x_j = (x_{j1}, \ldots, x_{jH})$. Thus, H variables on J objects are measured. Such information is summarized in the J × H matrix **X**, whose generic element is:

$$\|\mathbf{X}\|=\{x_{jh}\} \quad j=1,\ 2,\ \ldots,\ J\ ;\ h\ =\ 1,\ 2,\ \ldots,\ H$$

Introducing the object covariates, the entire information set for explaining the rating r_{ij} of the i-th subject on the j-th object becomes:

$$(r_{ij}\ \mid 1,\ y_{i1},\ \ldots,\ y_{ip}\ \mid 1, w_{i1}, \ldots,\ w_{iq}\ \mid x_{j1},\ \ldots,\ x_{jH})$$

and such information is related to model parameters by the systematic links:

$$\pi_{ij} = \left(\pi | \mathbf{y_i}, \mathbf{x_j}\right) = \frac{1}{1+\exp\left(-\mathbf{y_i}\boldsymbol{\beta} - \mathbf{x_j}\boldsymbol{\nu}\right)} \tag{4.16}$$

$$\xi_{ij} = \left(\pi | \mathbf{w_i}, \mathbf{x_j}\right) = \frac{1}{1+\exp\left(-\mathbf{w_i}\boldsymbol{\gamma} - \mathbf{x_j}\boldsymbol{\eta}\right)} \tag{4.17}$$

where $\boldsymbol{\nu}= (\nu_1, \ldots, \nu_H)'$ and $\boldsymbol{\eta}= (\eta_1, \ldots, \eta_H)'$ are further parameters to be estimated. Here, π_{ij} (ξ_{ij}) is related to uncertainty (feeling) expressed by the i-th subject, whose relevant characteristics are specified by y_i (w_i) when she/he is asked to rate the j-th object, whose characteristics are specified in turn by x_j (Kennet and Salini, 2011; Capecchi et al., 2016).

The innovative aspect of the CUB model is that it makes possible to break down the psychological mechanism of identifying the response into components and to identify the terms that influence each component. Object of research and interest are both the terms that influence the unconscious uncertainty and those who condition rational reasoning. Explaining the principles that move the individual psychological mechanism is a daunting and compelling challenge and it is even more if it is thought to hinge each of these principles in one of the aspects that move the individual in the process of choice.

4.4 Comparison between GLM and CUB Models

The main difference between the two introduced frameworks is that the first class of models assumes a multinomial distribution for the observed data derived by a latent construct (i.e. CLM and CLMM), whereas the second approach is explicitly oriented to explain and fit ordinal data by means of a mixture of given probability mass functions (i.e. CUB). Indeed, what is fundamental in the paradigm of GLM is the idea that ordinal data modelling requires cumulative functions to achieve ordered restraints on adjacent categories, and thus, any link with covariates may be expressed via distribution functions. Instead, the alternative CUB paradigm is based on a mixture distribution postulated to mimic the decision-making process of the observed ordinal score as driven by two main components, denoted as uncertainty and feeling (Piccolo et al., 2019).

The CLM (and CLMM) in general, work with ordinal quantitative dependent variables and involve the interpretation of results in terms of cumulative probabilities. Basically, assuming one wants to study the distribution of a given variable R (e.g. the overall comfort) with m categories ordered in an increasing sense, one goes to model the probability of observing a value of R less than or equal to j, indicating j a generic response category of R. This approach allows a comparison in terms of subject position, i.e. it allows to judge the effect on the response variable of the variation of the explanatory variables. On the other hand, it has the limitation of not considering the dispersion factor. In other words, a poor fit of the model can be caused by a variation of the dispersion at different values of the linear predictor.

The CUB model, whereas, is particularly adapted for the analysis of subjective evaluations it concurs to model separately the two components of feeling and uncertainty. Unlike in the Generalized Linear Model (GLM) in which covariates have an overall effect on the probability of each response category, in the CUB model, the influence of these on the response variable is mediated by the uncertainty and feeling components. This aspect makes the contribution of each explanatory factor more recognizable and allows to explain more effectively the complexity of the individual reasoning process.

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CHAPTER 5

This Chapter deals with the analysis of pressure distribution at user-seat interface. During seating, pressure and shear forces act on the passenger in all contact areas. Pressure is defined as the force acting perpendicularly on the surface unit F_p. The shear force is defined as the force acting parallel or tangentially to the surface unit F_s.

The combination of pressure, shear forces and friction determines the total load acting on the passenger's body, during seating. The load is not evenly distributed but it is concentrated at bony prominences where the contact area is rather small and the skin thinner, highly deformable but almost incompressible. In such areas, concentrated loads may be responsible for occlusion of blood flow and may lead to pressure ulcers, which correspond to mechanical damage to the tissues (Goossens, 2004).

When excessive pressure is applied to a contact area, cells react to the lack of oxygen in the tissue by releasing energy (glycolysis) which does not require oxygen. However, as the time for which cells can survive in anaerobic conditions is limited, it is not the pressure itself that causes ulcers but prolonged exposure to high loads or peaks of pressure. It has been shown, indeed, that the amount of pressure that can be applied to the skin without damaging the tissues decreases exponentially over time as shown in Figure 9 (Goossens and Rithalia, 2005) and this condition manifests itself most critically in the elderly passenger.

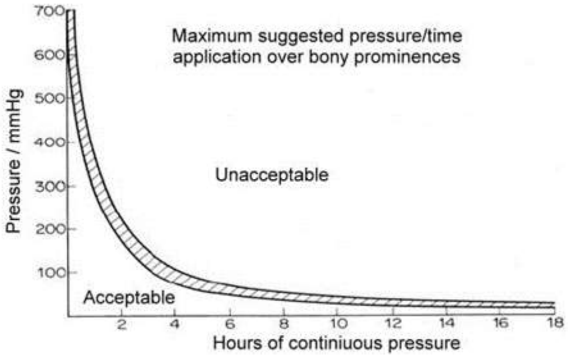

Figure 9. Pressure-Time Tolerance Curve- PTTC (Goossens and Rithalia, 2005)

It is noted that a pressure of the order of 120 mmHg can be tolerated for up to 4 hours, whereas a pressure of 200 mmHg falls into the region of unacceptability after 2 hours. In order to prevent pressure ulcers and reduce discomfort, considerable attention must be paid to the seat design : it must be equipped with a cushion allowing for correct pressure distribution at the user-seat interface with the applied contact pressure within the range [60 mmH-120 mmHg] (minimum and maximum blood pressure at heart level). It must also be able to distribute the weight of the torso evenly, provide a sufficiently large contact area and absorb shocks or vibrations (Campos and Xi, 2020).

5.1 Correlations between comfort and seat pressure measurements

The measurement of pressures generated at the seat-occupant interface is undoubtedly the most widely objective method used in industry to assess seating (dis-)comfort (Zemp et al., 2015), because it is less invasive and provides easily interpretable information. As introduced in Chapter 2, it is the objective method that shows the clearest association with (dis-)comfort scores (De Looze, 2003). In the field literature, although the correlation between pressure and subjective assessment has been investigated by several studies, no analysis has been carried out to take into account known disturbing factors on assessments or the fact that pressure data are collected under static conditions or in tests of short duration, nor have common (i.e. standardized) methodologies used to allow comparison of the different results obtained .The individual total load changes over time and the effects of seat properties on comfort seem to become apparent only after prolonged sitting time. The studies based on the correlation between pressure at the seat-occupant interface and discomfort are generally developed in automotive field or studied for office chairs. In the case of car seats in particular, a statistical relationship between pressure distribution and local discomfort has been found, and the results show that a more even distribution of pressure on the seat surface and a sufficiently high level of pressure at the lumbar back could certainly contribute to a reduction in perceived discomfort during sitting time. In the case of office chairs, a correlation was only established between lumbar pressure and local discomfort. It can be concluded, therefore, that incorporating pressure measures alongside subjective (dis-)comfort scores in the seat design process could lead to a considerable improvement in the ability of seats to meet the comfort needs of passengers. It is necessary to investigate whether such correlations could be extended to the field of air transport or public transport in general (De Looze et al., 2003).

5.2 Pressure mat

There are many technologies available for pressure measurement. The development of these techniques, as described in the studies conducted by Treaster and Marras (1987), began in the medical field, where it was necessary to quantify pressures at the interface to prevent pressure ulcers in subjects exposed to long hospital stays or with poor mobility. Pressure measurement tools, with appropriate industry modifications, were subsequently adopted in automotive and aircraft industries.

Pressure detection systems generally consist of four elements:

- a mat fitted with sensors;
- an electronic read-out which sends the data from the mat to a computer;
- a computer;
- software that processes this data (e.g. Mathematica or R-software).

The structure of the sensor mat can be very variable, and this variability depends on the number of sensors in the grid and the type of sensors used. Three types of sensors are widely used: resistive, capacitive and piezoresistive.

The main properties that a pressure detection system must have are as follows: repeatability, i.e. the ability of the measuring system to provide consistent measurement values each time it is used under the same conditions; sensitivity, which is characterized as the smallest value that can be recorded by the measuring instrument in question. It is required that the measuring instrument is sensitive, in order to assess how much the pressure values vary at different points on the mat.

5.2.1 Seat pressure indices

The pressure distribution at the seat occupant interface during seating can be described by means of pressure variables that represent synthetic indices of the distribution at the seat occupant interface.

Several indices are proposed in the literature. Which we will illustrate below, providing where possible also threshold values.

- **Peak pressure**

The peak pressure is the maximum pressure level measured over a predefined contact area. A review of the studies that have used the peak as an index for the pressure distribution shows that there is no single reference for threshold values. Kärki and Lekkala (2006); Shelton and Lott (2003); Stinson et al. (2013), identified 32 mmHg as the upper limit of sustainable whole-body pressure, because this value corresponds to capillary pressure at heart level. At higher pressures, the capillaries may be blocked, leading to a lack of oxygen in the tissues (the main culprit in the development of ulcers). However, this threshold value was challenged by Bar-Yam et al. (1998) who argued that it was too low a pressure level to be used as an upper pressure limit in the contact area of a seat. Bar also argued that it is not possible to set a single pressure threshold value for any part of the body in contact with a seat but that different thresholds should be used for different parts and for this reason he suggested that, specifically for the area of contact with the passenger's buttocks, the most accurate acceptable pressure value should be 60 mmHg. Sember (2020) suggested, for the ischial area, that the maximum sustainable pressure threshold, after 15 minutes of testing, is 62mmHg. Kamijo et al. (1982), indicated characteristic values for identifying a comfortable car seat. They associated the lumbar region of the backrest with a pressure range from 1.4 kPa (10.5 mmHg) to 2.3 kPa (17.2 mmHg), considering pressure values above 18 mmHg unacceptable for this area.

From the results of literature studies using peak pressure, it is possible to outline the main critical issues associated with the use of this pressure index:

- It is not possible to identify a threshold value, which is valid for the whole body. Each area of the body will have a different limit of tolerance to pressure, e.g. the buttocks area has the capacity to tolerate higher pressure loads than the buttocks area. To overcome this problem, different thresholds can be set for different contact areas (Kamijo et al 1982; Kolich,2004; Oudenhuijzen et al.,2003).

- Once the contact area of interest is fixed, a single pressure value is not sufficient to describe a pressure distribution in that area. This implies that referring to a maximum pressure value results in the loss of a large amount of information content in the data (Hiemstra-van-Mastrigt, 2017).
- Peak pressure is not a reliable indicator for seat comparisons. Studies show that it only allows us to detect differences in terms of (dis)comfort between seats with extreme differences in shape and upholstery (e.g. a seat with a wooden surface compared to a seat with a cushion). On the other hand, if we limit ourselves to comparisons between seats belonging to the same seating category, differences in subjective evaluations of comfort are not reflected in the peak values measured.

This is also supported by the study conducted by Porter in 2003. In this study, three different car seats were selected, and peak pressures were measured for each of them in six different contact areas (right ischial area, left ischial area, right thigh, left thigh, upper back, middle-lower back).

The peaks were significantly different between the three seats only in one contact area (left ischial area), although the results from the analysis of the comfort questionnaires showed differences in all areas. Therefore, if one wished to construct a predictive model of comfort through pressure measurements, such a model should incorporate other variables in addition to the peak in order to obtain more accurate predictions (Porter et al., 2003; Hiemstra-van-Mastrigt S., 2017).

From the peak, it is possible to construct synthetic indicators linked to it:

- Mean peak pressure (MPP): average over time of the peaks associated with a contact area (Carcone and Keir, 2007). It allows the variations of the peak detected over time to be taken into account

- Average peak per area: average of the peaks detected in fixed area calculated on a sample of participants (Kyung and Nussbaum, 2008). Allows for variations in the peak in relation to anthropometric variations of the participants;
- Average local peak/sum of average peaks: ratio between the average local peak (for a given contact zone) and the sum of the average peaks associated with all the contact zones considered (Kyung and Nussbaum, 2008);
- Minimum pressure/maximum pressure: ratio between the minimum pressure measured in a contact area and the maximum pressure in the same area (Gyi and Potter, 1999);
- Minimum ratio: ratio of the second highest pressure in a specific area to the peak pressure in the same area

- **Mean Pressure**

The mean pressure is the average of the pressure levels measured over a fixed contact area. Regarding the recommended mean pressure values we can refer to Kamijo et al. 1982. They set the range of variation for the lumbar area between 11 mmHg and 18 mmHg, the recommended mean pressure for the ischial area below 43.5 mmHg and for the other regions of the body they recommend a mean pressure of around 22 mmHg.

Regarding the characteristics of this index, the following critical points were observed.

- The mean pressure has the advantage over the peak pressure of providing a value that also considers the information content coming from the lower pressure levels affecting the area considered. However, as in the case of the peak, it does not allow a full description of the pressure distribution generated in that area.
- The mean pressure, like the peak pressure, is not a good index for the comparison between seats. Compared to the peak, it is an indicator with a higher level of sensitivity for discrimination, but still not able to differentiate between seats with similar comfort performance. This is confirmed by the results of Porter's 2003 study, already mentioned in the previous paragraph. In that study,

mean pressures, as opposed to peaks, allowed for statistically significant differences in 3 contact areas out of a total of 6 selected areas (left ischial area, left thigh and right thigh), but still failed to be fully explanatory of the comfort judgements made by the participants. Again, if one wished to construct a predictive model of comfort through pressure measurements, even for mean pressure, such a model would have to incorporate other variables in addition to it to obtain more accurate and statistically relevant predictions (Hiemstra-van-Mastrigt S.,2017).

The indices related to mean pressure are:

- Average seat ratio: indicates the ratio between the mean pressure measured in one contact area and the mean pressure measured in another area;
- Local mean pressure /total mean pressure: ratio between average pressure relative to a local area and the total average pressure intended as the sum of the average pressures associated with all the contact areas considered.

- **Distributed load percentage**

Distributed load percentage means the fraction of the total human body load acting on the seat (or any part of it) or alternatively the percentage of load transferred through the seat to a particular region of the body. Values may be expressed in [kg] or in terms of % of total body weight. To show the function of this indicator, it is possible to refer to the study conducted by Andreoni et al. 2002, which shows its purpose. Ideally dividing the body into three parts: thorax (upper area); pelvis (lower area) and lumbar area (intermediate area); we calculate the percentage of load transferred by the seat on each anatomical area and the percentage of load exerted by each subject on a specific part of the seat. The values obtained are shown in the table and correspond to the average of the values associated to the single subjects of the examined sample.

By examining the percentages of load distributed over the body, it is possible to establish which areas of the body are most exposed to high loads. In this case, it was found that most of the load transferred by the seat is exerted on the pelvis (about 67% on average).

Table 3. Load transferred

Load transferred	**Mean**	**Standard Deviation**
Seat pan load (kg)	31	9
Backrest Load (kg)	15	3
Seat Load (% total weight)	63	13
Seat pan load (% total weight)	43	11
Backrest load (% total weight)	20	4

By examining the load values transferred through the seat (Table 3), it is possible to identify the parts of the seat that interact most with the body and on which the highest loads are concentrated. Mergl (2006) and Zenk et al. (2007) in a study of car seats used discomfort scores from questionnaires to determine the ideal pressure distribution to be used in the design of a premium seat. After ideally dividing the seat into main contact areas they determined the corresponding ideal load percentage to be applied:

Table 4. Results of studies by Zenk (2007) and Mergl (2006)

Contact Area	**Distributed load percentage**
Upper bacjrest area	20-50%
Back of the seat pan	49-50%
Middle of the seat pan	<28%
Front of the seat pan	6%

Examination of the distributed load values (Table 4) shows that an ergonomic seat is able to distribute the total load in such a way that a preponderant percentage is concentrated below the buttocks and the least load is applied below the end of the thighs, at the knees

5.3 Factors affecting seat pressure distribution

5.3.1 Seat features

The literature review investigating the correlation between seat features and pressure distribution showed that eight of the nine studies analyzed found associations between seat size/shape and pressure. Kyung and Nussbaum (2008) verified that seats with different characteristics in terms of size of individual parts, shape and cushion upholstery materials show significant effects on some pressure variables such as peak and contact area detected for buttocks and thighs. Reed et al. (2000) examined the impact of cushion length on pressure distribution at the thighs. They observed that a pillow that is too long in relation to the size of its occupant is responsible for a concentration of pressure on the thigh end zone adjacent to the knees with potential obstruction of blood flow to the legs. Respect to the seat shape, Makhsous et al. (2007) showed that different cushion shapes generate different pressure distributions at the interface, and based on this principle, Noro et al. (2012) compared a new prototype surgical seat with a standard one. The new prototype was characterized by innovative shape able to follow the contour of the human body in the buttocks-sacral area. Examination of the pressure variables measured for the new seat showed a larger contact area and a lower mean total pressure, confirming a change in pressure variables due to the change in seat shape. None of the studies mentioned calculated the correlation coefficient between seat features (size, shape and materials) and interface pressure, and no quantitative relationship was found. However, they show the existence of significant associations to be considered in the design. The seat-user pressure distribution is highly dependent on the density of the foam of which the seat is made. In relation to seat design parameters such as backrest angle and seat pan angle, a change in these angles is responsible for a redistribution of pressures at the interface: Hostens et al. (2001) demonstrated that a smaller backrest angle results in an increase in pressure on the seat pan and a reduction in pressures on the backrest.

5.3.2 User characteristics

The experiment carried out by Porter and Gyi (1999), in line with the results produced previously by Yang et al. (1984), shows that gender plays a significant role in how pressures are distributed at the seat-occupant interface. Porter and Gyi's (1999) experiment found that males typically had higher contact pressure values than females with particular evidence below the IT area and in the thigh area. For this reason, the factors "sex" and "hip width" (which is also sex-dependent) are shown, following a multiple regression analysis, to be the best predictors of mean pressure in the IT area (Porter and Gyi, 1999). Zacharkow (1988) suggested that males might exhibit higher levels of contact pressure because they have less subcutaneous fat at the buttocks and hips, they are heavier around the pelvic area and the IT zones are closer to the ischial area. In contrast, the study by Park et al. (2013) found no significant correlation between gender and pressure variables.

In order to examine the correlation between age and pressure distribution, it is possible to refer to the study by Kyung and Nussbaum (2013), whose contents and results are briefly shown in Table 5.

Table 5. Kyung and Nussbaum (2013)

Pressure variable	**Correlation**	**Study design**	**Conclusion**
Average contact area and ratio of local contact area to global contact area for 6 body regions: right/left thigh, right/left buttock, upper/lower back.	Older drivers show a higher average contact area for the right buttock of 12.9%. Younger drivers show a higher contact ratio of 7.3% for the left thigh.	N=22 drivers divided into two age groups: elderly (>60 years, N=11) and young (20-35 years, N=11). 6 driving sessions: combination of vehicle classes (sedan/SUV), driving conditions (lab/field) and seat (two comfort levels)	A significant effect of age was found for four of the 36 pressure measures considered. Different loads were attributable to postural differences between the two categories of drivers.
Local mean pressure and ratio of local mean pressure to local mean pressure (assessed for each local area considered)	Average contact pressure in the lower back for young drivers is 30.8% higher than for older drivers		
Ratio of the local average peak to the sum of the average peaks (evaluated for each of the 6 local areas considered)	The peaks ratio in the upper back for young drivers is 13.9% higher than that observed for older drivers		

Several studies (Vos et al., 2006; Moes, 2007; Jackson et al., 2009; Kyung and Nussbaum, 2009) have examined the observable correlation between pressure distribution at the seat-occupant interface and occupant anthropometric data. Some of these studies, instead of considering 'pure' anthropometric data, have opted for the construction of synthetic indicators, e.g. BMI, in order to jointly take into account more data (Table 6).

Table 6. Studies about the correlation between pressure distribution at the seat-occupant interface and occupant anthropometric data

Bibliography	**Antrhopometric variable**	**Variabile di pressione**	**Correlation**	**Study Design**	**Conclusions**
Jackson et al. 2009	BMI	Peak pressure	Not significant correlation	5 different seat cushions for gliders. N=35 glider pilots with height less than 1.85m. Simulated flight of 1.5 h	There was no significant correlation between BMI, mass, height and mean peak pressure.
	Height				
	Weight				
Hostens et al. 2001	BMI	Mean pressure	$R^2 = 0.8881$	4 foam-filled and 1 air-filled sessions. N=10 male participants. The experiment was developed in 4 phases of two minutes with two minutes of pause with feet freely arranged	Almost linear relationship between mean blood pressure and BMI
		Peak pressure	Not significant correlation		No significant correlation between peak blood pressure and BMI
Kyung and Nussbaum 2009	Height (low/medium/high)	Average contact area right buttock	The group of tall participants has a larger contact area for the right thigh	Sitting of a car driver. N= 27 participants (12 males and 15 females). 6 driving sessions of 15-20 minutes each. 2x2x2 type design (session x vehicle class x driving type)	A significant effect of stature emerged only with three pressure variables that were correlated with mean contact area and ratio.
		Average contact area right buttock	The group of tall participants have a larger contact area for the upper back		
		Ratio of average contact areas (upper back area/total area)	The group of tall participants has a larger area ratio for the upper back		

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CHAPTER 6

In this chapter the Experiment conducted at TU Delft is described and analyzed; the main results are discussed.

6.1 The effect of aircraft seat pitch on seating (dis-)comfort

Population aging has become a notable and enduring demographic phenomenon in most countries, especially in Europe and North America: by the year 2025 it is expected to double its present size (Rosenbloom, 2001). By 2051, the projected population of people aged 65 years and over is expected to be at least double its size in 1999 (ABS, 2001). At the same time, improved living conditions and advances in medicine have extended life expectancy and quality of life, resulting an increasing number of elderly travelers. These changes in the composition of the population and in the elderly habits will provide new challenges for the provision of transportation services, especially because the travel patterns and needs of the elderly travelers are likely to become more complex (Alsnih et al., 2003). The transportation system will have to start focusing more closely on understanding their mobility and accessibility needs: ageing brings several normal physical changes and sometimes is accompanied by diseases that affect physical functions and abilities.

Focusing on travelling by plane, the elderly require special consideration in the design of seat and aircraft space. The elderly travelers are more likely to have restricted physical mobility or diseases that limit movements and, according to the European regulations on airline, is required to make all reasonable efforts to arrange seating to meet the needs of a person with reduced mobility (PRM) subject to safety requirements and availability (Regulation EC N. 1107/2006). Many airlines solve this by developing recommendations and advice aimed at helping elderly travelers, by assigning special seats to the PRMs, offering comprehensive assistance to the elderly at airports, support them with in – and egress, having seats with movable aisle armrests to facilitate convenient transfer from the wheelchair to the seat and offering special menus aboard the flight (Vink et al., 2014; Ramos-Sesma et al., 2018). These are customized solutions that can be adopted if necessary, while it would be useful to be able to meet the needs of all passengers with an appropriate design of the seats and the aircraft environment that also takes into account the emerging needs of elderly travelers in order to provide a comfortable journey, but research in this direction is still limited.

According to the Oxford Dictionaries, comfort can be described as a state of physical ease and freedom from pain and constraint, whereas the scientific literature offers a variety of definitions. Pineau (1982), for example, included everything that contributes to human well-being and convenience of the material aspects of life in his definition of comfort; for Kremser et al. (2012), comfort is not simply the absence of discomfort: comfort and discomfort can even occur at the same time. Specifically, discomfort is more related to objective physical measures, whereas comfort relates to psychological well-being (De Looze et al, 2003). All these definitions highlight several issues suggesting that comfort should be viewed as a subjective and personal state which results from a reaction to the environment and is influenced by psychological, physiological and physical factors. As well as a variety of comfort definitions, in the specialized literature there are also several conceptual comfort models that aim to explain how the comfort experience develops: the theoretical model of (dis-)comfort by De Looze, Kuijt-Evers, and Van Dieën (2003) distinguishes three levels: human, seat and context levels. At a context level, not only the physical features are assumed to play a role, but also psycho-social factors like for example job satisfaction and social support. At a seat level, the aesthetic design of a seat in addition to physical features may affect the feelings of comfort. At human level the influential factors are assumed to be individual expectation and other individual feelings or emotions. The model proposed by Vink and Hallbeck (2012) defines 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. Based on this definition, the (dis-)comfort model simplifies the steps that influence the (dis-)comfort experience making clear the genesis of this experience: the interaction caused by a contact between a product (the seat for example) and the passenger starts in the aircraft environment where the passenger is doing a specific task (activity). This interaction can result in internal human body effects (e.g. changes in the human sensors, tactile sensations, body posture change, blood flow changes and muscle activation). The perception effects are influenced by the human body effects, but also by expectations. The final outcomes may be feelings of (dis-)comfort or no feelings.

Focusing on passenger comfort, in order to improve the passenger experience, it is necessary to understand what factors influence the seat comfort experience and whether they are the same for young travelers as for elderly travelers. In the last decades, the scientific literature on human factors and ergonomics has widely investigated the topic of comfortable and optimized seating, focusing mainly on office seats (e.g. Bazley et al., 2015; Groenesteijn et al., 2015; Van Dieën et al., 2001) or automotive seats (e.g. Franz, 2010; Zenk et al., 2006). Scientific papers on passenger seats in public transport are much less common (e.g. Han et al., 1998; Lee et al., 2009; Park et al., 2014).

Vink et al. (2012) found a strong correlation (r = 0.73) between comfort and “fly again with the same airlines and showed that legroom (r = 0.72) has a high correlation with comfort. Kremser et al. (2012) found the influence of seat pitch to passenger well-being; Moerland et al. (2015) made a hypothetical model on the relationship of seat pitch, seat width and comfort; Li et al. (2017) found that there is a relationship between seat pitch and sitting comfort; Anjani et al. (2018), showed that the comfort related to seat distances is related to human anthropometry. So, it is clear that, the arrangement of the seat pitch will affect the legroom or knee space; in Figure 10 the measures seat pitch and legroom are shown. Seat pitch is defined as the distance from a point on the seat in one row to the same point on a seat in the next row. The depth and the contour of the backrest reduce seat pitch to the available legroom.

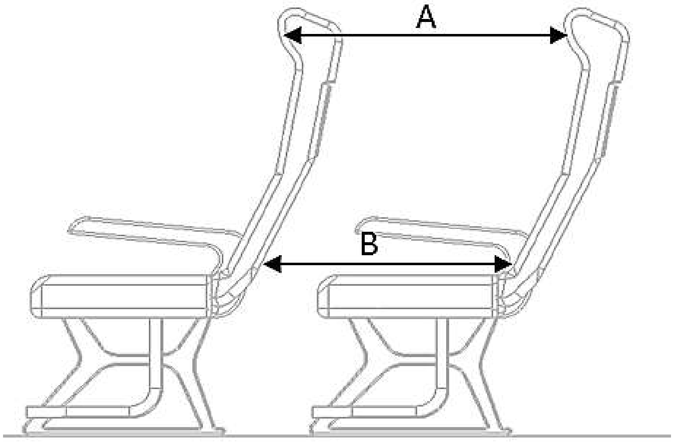


Figure 10. Seat pitch (A) and Legroom (B)

Providing sufficient legroom enables passengers to stretch legs which result in a changing body posture as a way to prevent discomfort and it is an important factor for frequent flyers' level of satisfaction. (Vink, 2016). The experiments will consist of a comfort comparative assessment of 3 typical seat-pitch conditions and will be conducted in a fuselage. The main idea is evaluating the comfort experience in terms of accessibility and seat comfort. The methods with which the experimentation will be conducted and the research objectives pursued, are detailed below.

6.2 Experimental Study

The study involved a total of 20 participants (10 males, 10 females) in fuselage test sessions for the evaluation of the seating (dis-)comfort of 3 aircraft seat pitch conditions. Procedures for participant recruitment and data collection were defined considering ethical considerations and it was approved by the Human Research Ethical Committee at Delft University of Technology (HREC, TU Delft), in the Netherlands. Before providing the informed consent, participants were fully informed on the type, number and duration of experimental sessions, as well as on the research aims and the treatment of the collected data.

6.2.1 Participants

Participants were required to be free from severe musculoskeletal disorders (MSDs) in the last year, to have taken at least one flight in the last two years, to be independents in movements and to be economy class flyers. In order to ascertain the above requirements, volunteers were asked to fill an informative questionnaire and a MSDs checklist so as to provide information on location, intensity and duration of any musculoskeletal injury experienced in the last year. Before the start of the tests, several anthropometric data were collected. The range, mean and standard deviation (SD) of the participant main anthropometric characteristics (viz. age, height, weight, and Body Mass Index-BMI) are reported in Table 7. All participants were in good physical and mental health.

Table 7. Main anthropometric characteristics of elderly participants

	Num.	Age [year] [min-max]	Weight [kg] [min-max]	Height [m] [min-max]	BMI [kg/m^2] [min-max]
Males	10	[66-85]	[71-105]	[1.70-1.91]	[21.2-30.4]
Mean (SD)		72.4 (5.23)	87.5 (8.94)	1.80 (0.06)	27.16 (3.04)
Females	10	[61-72]	[54-95]	[1.60-1.85]	[18.2-29.2]
Mean (SD)		67.6 (3.5)	68.5 (12.9)	1.67 (0.07)	24.2 (3.8)

6.2.2 Test conditions

The experimental study was conducted in a Boeing 737 airplane located at the campus of Delft University of Technology. The airplane had 3-3 configuration but the tests were performed only in one side of the fuselage. Participants assessed the (dis-)comfort of 3 economy class seat pitches: 28 inches, 30 inches and 32 inches (Figure 11).

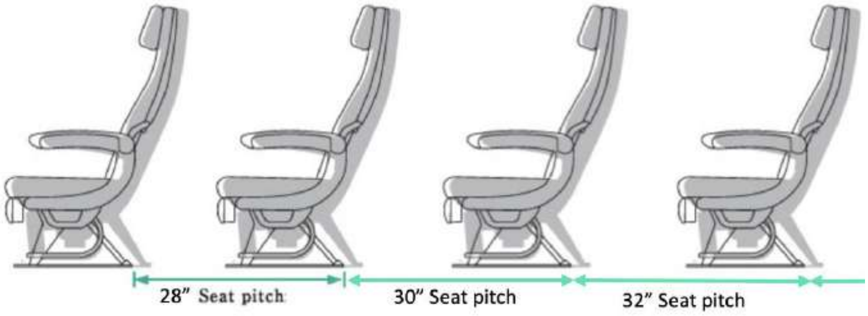


Figure 11. Seat pitches tested

The seat pitch sizes selected for the experiments were based on the sizes currently adopted for economy class flights and comparable with findings in the field literature (Anjani et al., 2020; Vanacore et al., 2019; Li et al., 2017; Kremser et al., 2012). The seats used for the test were the same and they were economy class seats.

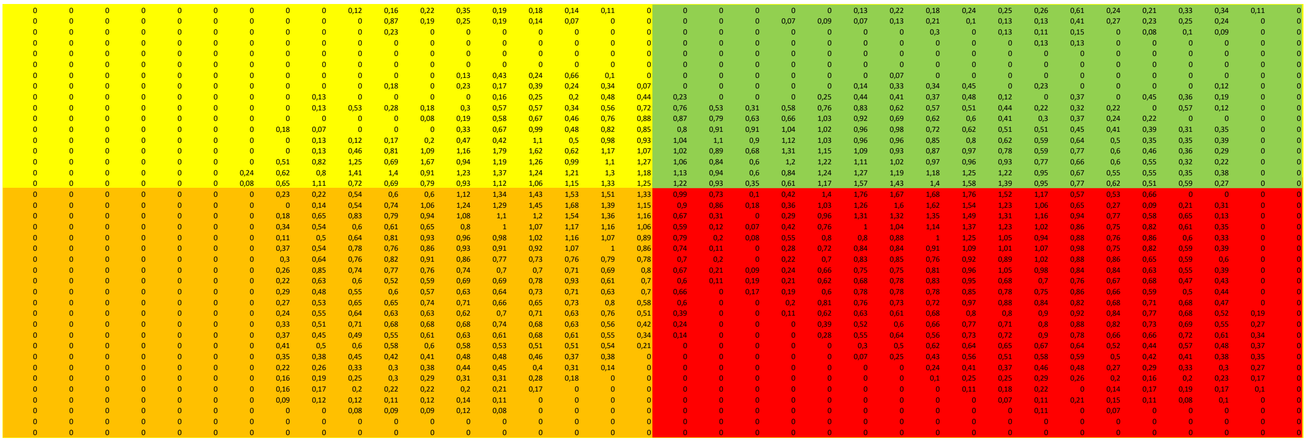
6.2.3 Subjective and Objective Measurements

Subjective evaluations were collected, asking participants to fill in the questionnaire about seating (dis-)comfort experience, at fixed time intervals. Specifically, local discomfort perceptions were collected using a body discomfort map and a scale for perceived discomfort intensity (CR-10 scale; Borg, 1982). The map consists of 19 body parts; it was adapted from the body map proposed by Corlett et al. (1986). The CR-10 scale is recognized as a valid and reliable scale for evaluating seat discomfort (Shen and Parsons, 1997) and it is widely adopted in experimental studies on seating discomfort in combination with body maps. Global and local comfort perceptions were collected using a questionnaire consisting of 16 comfort questions: the first 9 comfort questions addressing the overall comfort attributes and specific seat pan and backrest comfort attributes (e.g. “Is the cushion padding comfortable?”); the comfort questions from 10 to 14 addresses the legroom comfort (i.e. “Is there enough room to get in and out of the seat?”); the last two comfort statements addresses the arm comfort (i.e. “How would you rate the height of armrest?”). Subjects were asked to assign to each one a score between 0 and 10 (no comfortable-extreme comfortable). Both the discomfort and comfort questionnaire were translated in Dutch to avoid comprehension problems when participant filling in the questionnaires (Figure 12).

Figure 12. A female participant answering the questionnaire

Occupant-seat interface pressures were collected continuously during each test session, using one calibrated XSENSOR flexible inducted pad. The output of the pad is 48 × 48 dot matrix of pressure. It uses capacitive technology to test pressure. The range of the pressure is from 10 mmhg to 200 mmhg, and the number of sensors 2560. Pressures were recorded at a frequency of 40 Hz. The pressure distribution was collected only for the seat pitch fixed at 32 inches.

Pressure data from the mat were divided into four body regions (left/right buttock and left/right thighs, Figure 13). Values of interest were mean pressure (average of all sensor values), average contact area and peak pressure.



0	0	0	0	0	0	0	0	0	0,12	0,16	0,22	0,35	0,19	0,18	0,14	0,11	0	0	0	0	0	0	0,13	0,22	0,18	0,24	0,25	0,26	0,61	0,24	0,21	0,33	0,34	0,11	0
0	0	0	0	0	0	0	0	0	0	0,87	0,19	0,25	0,19	0,14	0,07	0	0	0	0	0	0,07	0,09	0,07	0,13	0,21	0,1	0,13	0,13	0,41	0,27	0,23	0,25	0,24	0	0
0	0	0	0	0	0	0	0	0	0	0,23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,3	0	0,13	0,11	0,15	0	0,08	0,1	0,09	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,13	0,13	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0,13	0,43	0,24	0,66	0,1	0	0	0	0	0	0	0	0,07	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0,18	0	0,23	0,17	0,39	0,24	0,34	0,07	0	0	0	0	0	0,14	0,33	0,34	0,45	0	0,23	0	0	0	0	0,12	0	0
0	0	0	0	0	0	0	0	0,13	0	0	0	0	0,16	0,25	0,2	0,48	0,44	0,23	0	0	0	0,25	0,44	0,41	0,37	0,48	0,12	0	0,37	0	0,45	0,36	0,19	0	0
0	0	0	0	0	0	0	0	0,13	0,53	0,28	0,18	0,3	0,57	0,57	0,34	0,56	0,72	0,76	0,53	0,31	0,58	0,76	0,83	0,62	0,57	0,51	0,44	0,22	0,32	0,22	0	0,57	0,12	0	0
0	0	0	0	0	0	0	0	0	0	0	0,08	0,19	0,58	0,67	0,46	0,76	0,88	0,87	0,79	0,63	0,66	1,03	0,92	0,69	0,62	0,6	0,41	0,3	0,37	0,24	0,22	0	0	0	0
0	0	0	0	0	0	0	0,18	0,07	0	0	0	0,33	0,67	0,99	0,48	0,82	0,85	0,8	0,91	0,91	1,04	1,02	0,96	0,98	0,72	0,62	0,51	0,51	0,45	0,41	0,39	0,31	0,35	0	0
0	0	0	0	0	0	0	0	0,13	0,12	0,17	0,2	0,47	0,42	1,1	0,5	0,98	0,93	1,04	1,1	0,9	1,12	1,03	0,96	0,96	0,85	0,8	0,62	0,59	0,64	0,5	0,35	0,35	0,39	0	0
0	0	0	0	0	0	0	0	0,13	0,46	0,81	1,09	1,16	1,79	1,62	0,62	1,17	1,07	1,02	0,89	0,68	1,31	1,15	1,09	0,93	0,87	0,97	0,78	0,59	0,77	0,6	0,46	0,36	0,29	0	0
0	0	0	0	0	0	0	0,51	0,82	1,25	0,69	1,67	0,94	1,19	1,26	0,99	1,1	1,27	1,06	0,84	0,6	1,2	1,22	1,11	1,02	0,97	0,96	0,93	0,77	0,66	0,6	0,55	0,32	0,22	0	0
0	0	0	0	0	0	0,24	0,62	0,8	1,41	1,4	0,91	1,23	1,37	1,24	1,21	1,3	1,18	1,13	0,94	0,6	0,84	1,24	1,27	1,19	1,18	1,25	1,22	0,95	0,67	0,55	0,55	0,35	0,38	0	0
0	0	0	0	0	0	0,08	0,65	1,11	0,72	0,69	0,79	0,93	1,12	1,06	1,15	1,33	1,25	1,22	0,93	0,35	0,61	1,17	1,57	1,43	1,4	1,58	1,39	0,95	0,77	0,62	0,51	0,59	0,27	0	0
0	0	0	0	0	0	0	0,23	0,22	0,54	0,6	0,6	1,12	1,34	1,43	1,53	1,51	1,33	0,99	0,73	0,1	0,42	1,4	1,76	1,67	1,68	1,76	1,52	1,17	0,57	0,53	0,66	0	0	0	0
0	0	0	0	0	0	0	0	0,14	0,54	0,74	1,06	1,24	1,29	1,45	1,68	1,39	1,15	0,9	0,86	0,18	0,36	1,03	1,26	1,6	1,62	1,54	1,23	1,06	0,65	0,27	0,09	0,21	0,31	0	0
0	0	0	0	0	0	0	0,18	0,65	0,83	0,79	0,94	1,08	1,1	1,2	1,54	1,36	1,16	0,67	0,31	0	0,29	0,96	1,31	1,32	1,35	1,49	1,31	1,16	0,94	0,77	0,58	0,65	0,13	0	0
0	0	0	0	0	0	0	0,34	0,54	0,6	0,61	0,65	0,8	1	1,07	1,17	1,16	1,06	0,59	0,12	0,07	0,42	0,76	1	1,04	1,14	1,37	1,23	1,02	0,86	0,75	0,82	0,61	0,35	0	0
0	0	0	0	0	0	0	0,11	0,5	0,64	0,81	0,93	0,96	0,98	1,02	1,16	1,07	0,89	0,79	0,2	0,08	0,55	0,8	0,8	0,88	1	1,25	1,05	0,94	0,88	0,76	0,86	0,6	0,33	0	0
0	0	0	0	0	0	0	0,37	0,54	0,78	0,76	0,86	0,93	0,91	0,92	1,07	1	0,86	0,74	0,11	0	0,28	0,72	0,84	0,84	0,91	1,09	1,01	1,07	0,98	0,75	0,82	0,59	0,39	0	0
0	0	0	0	0	0	0	0,3	0,64	0,76	0,82	0,91	0,86	0,77	0,73	0,76	0,79	0,78	0,7	0,2	0	0,22	0,7	0,83	0,85	0,76	0,92	0,89	1,02	0,88	0,86	0,65	0,59	0,6	0	0
0	0	0	0	0	0	0	0,26	0,85	0,74	0,77	0,76	0,74	0,7	0,7	0,71	0,69	0,8	0,67	0,21	0,09	0,24	0,66	0,75	0,75	0,81	0,96	1,05	0,98	0,84	0,84	0,63	0,55	0,39	0	0
0	0	0	0	0	0	0	0,22	0,63	0,6	0,52	0,59	0,69	0,69	0,78	0,93	0,61	0,7	0,6	0,11	0,19	0,21	0,62	0,68	0,78	0,83	0,95	0,68	0,7	0,76	0,67	0,68	0,47	0,43	0	0
0	0	0	0	0	0	0	0,29	0,48	0,55	0,6	0,57	0,63	0,64	0,73	0,71	0,63	0,7	0,66	0	0,17	0,19	0,6	0,78	0,78	0,78	0,85	0,78	0,75	0,86	0,66	0,59	0,5	0,44	0	0
0	0	0	0	0	0	0	0,27	0,53	0,65	0,65	0,74	0,71	0,66	0,65	0,73	0,8	0,58	0,6	0	0	0,2	0,81	0,76	0,73	0,72	0,97	0,88	0,84	0,82	0,68	0,71	0,68	0,47	0	0
0	0	0	0	0	0	0	0,24	0,55	0,64	0,63	0,63	0,62	0,7	0,71	0,63	0,76	0,51	0,39	0	0	0,11	0,62	0,63	0,61	0,68	0,8	0,8	0,9	0,92	0,84	0,77	0,68	0,52	0,19	0
0	0	0	0	0	0	0	0,33	0,51	0,71	0,68	0,68	0,68	0,74	0,68	0,63	0,56	0,42	0,24	0	0	0	0,39	0,52	0,6	0,66	0,77	0,71	0,8	0,88	0,82	0,73	0,69	0,55	0,27	0
0	0	0	0	0	0	0	0,37	0,45	0,49	0,55	0,61	0,63	0,61	0,68	0,61	0,55	0,34	0,14	0	0	0	0,28	0,55	0,64	0,56	0,73	0,72	0,9	0,78	0,66	0,66	0,72	0,61	0,34	0
0	0	0	0	0	0	0	0,41	0,5	0,6	0,58	0,6	0,58	0,53	0,51	0,51	0,54	0,21	0	0	0	0	0	0,3	0,5	0,62	0,64	0,65	0,67	0,64	0,52	0,44	0,57	0,48	0,37	0
0	0	0	0	0	0	0	0,35	0,38	0,45	0,42	0,41	0,48	0,48	0,46	0,37	0,38	0	0	0	0	0	0	0,07	0,25	0,43	0,56	0,51	0,58	0,59	0,5	0,42	0,41	0,38	0,35	0
0	0	0	0	0	0	0	0,22	0,26	0,33	0,3	0,38	0,44	0,45	0,4	0,31	0,14	0	0	0	0	0	0	0	0	0,24	0,41	0,37	0,46	0,48	0,27	0,29	0,33	0,3	0,27	0
0	0	0	0	0	0	0	0,16	0,19	0,25	0,3	0,29	0,31	0,31	0,28	0,18	0	0	0	0	0	0	0	0	0	0,1	0,25	0,25	0,29	0,26	0,2	0,16	0,2	0,23	0,17	0
0	0	0	0	0	0	0	0,16	0,17	0,2	0,22	0,22	0,2	0,21	0,17	0	0	0	0	0	0	0	0	0	0	0	0,11	0,18	0,22	0	0,14	0,17	0,19	0,17	0,1	0
0	0	0	0	0	0	0	0,09	0,12	0,12	0,11	0,12	0,14	0,11	0	0	0	0	0	0	0	0	0	0	0	0	0	0,07	0,11	0,21	0,15	0,11	0,08	0,1	0	0
0	0	0	0	0	0	0	0	0	0,08	0,09	0,09	0,12	0,08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,11	0	0,07	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 13. An example of seat pressure map divided in the four areas (left/right buttock and left/right thighs)

6.2.4 Experimental Protocol

In one side of the fuselage, the seat pitches of 4 rows, each one with three seats, were fixed at 28, 30 and 32 inches. The first row was fixed at 28 inches, the second one at 30 inch and the last two rows at 32 inches. Each test session lasted about 40 min. During each test session the participant performed an activity of her/his choice, with a posture that she/he found comfortable, with the seat in upright position. Two types of tests were performed by the participants.

In the first type of test each participant assess the different seat pitches conditions, sitting in the middle seat, and (dis-)comfort perceptions were collected; in the second type of test, for each participant seated in the middle seat with a seat pitch fixed at 32 inches, pressure distributions and discomfort perceptions were collected. Participants wore comfortable clothes without heavy seams, buttons or pockets to minimize the impact of clothing on the pressure readings.

Subjective (dis-)comfort evaluations were collected at fixed time intervals. At the beginning (T_0), in the middle (T_1) and at the end (T_2) of each test session. To reduce muscle fatigue, there was a break (1 hour) between two successive tests conditions.

Before the start of the test, participants received a verbal explanation of the research protocol. Each day a group of maximum 4 participant were involved in the experiment.


[redacted]
[redacted]

Figure 14. Participants during fuselage tests

6.2.5 Experimental plan

The test sessions were planned via a Williams design (Jones and Kenward, 2014) taking into account the main noise factors: day of the week, time of the day and inter-individual variability which could impact on (dis-)comfort assessment. Specifically, the 20 test sequences were defined using a 5 × 5 Latin square with 4 replications and then assigned randomly to participants. A time of one hour was set between two successive tests as a wash out period and to allow the participant to rest and stretch their legs.

6.2.6 Statistical data analysis

Statistical data analysis aimed at investigating the differences in perceived comfort among seat pitches analyzed; the gender-based differences and the effects of sitting duration in perceived local discomfort for different seat pitches.

Differences in perceived comfort among the three different seat pitches were tested via Kruskall-Wallis test and Wilcoxon Matched-Pairs Signed Ranks test was adopted for post hoc pairwise comparisons with p-value adjusted using Bonferroni's correction. Gender-based differences in perceived local discomfort were tested via Mann Whitney test using the discomfort scores collected at T_2. Effects of sitting duration on perceived discomfort were analyzed via Wilcoxon Signed Ranks test on local discomfort scores collected at T_0, T_1 and T_2. The distribution of the occupant-seat interface pressure was analyzed statically by synthetic pressure distribution index (i.e. peak pressure and mean pressure). In order to investigate the relationship between objective and subjective measures of overall and local (dis-)comfort, the values of mean pressure and peak pressure, for seat pan were correlated to 6 indicators of perceived discomfort: discomfort at the head, discomfort at arms, discomfort at back, discomfort at buttocks, discomfort at thighs and discomfort at feet. The correlation analysis was carried out with respect to both the average discomfort for these areas and the total discomfort obtained as the sum of the scores for these areas. All statistical tests were considered “significant” for p-value ≤ 0.05.

6.3 Results

The comfort data distribution in three times analyzed among the seat pitches conditions were shown in Figure 15. Significant differences in perceived comfort among seat pitch conditions were found by Kruskal Wallis test.

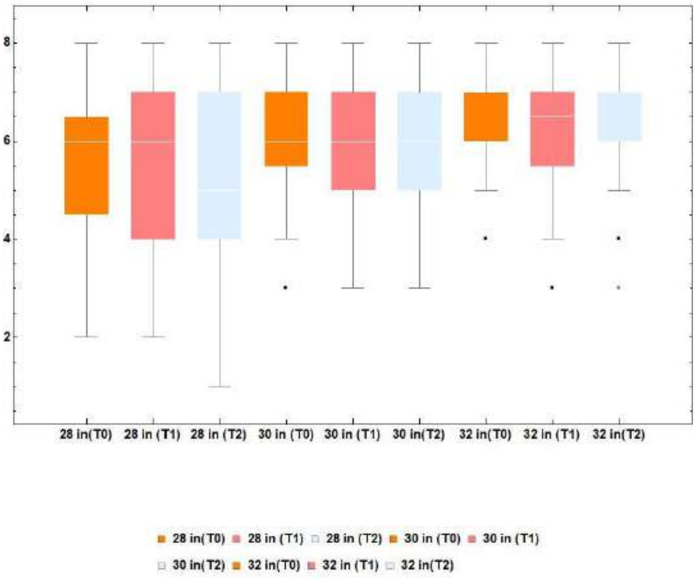


Figure 15. Comfort data distribution in three times analyzed among the seat pitches conditions

The post hoc analysis via Wilcoxon Matched-Pairs Signed Ranks test pointed out that seat pitch fixed at 28 in obtained the worst evaluation for the overall comfort (28 vs 30, p value = 0.02; 28 vs 32, p value = 0.008), already at the first detection time.

The results of Mann Whitney test for gender-based differences on local discomfort (Table 8) reveal that females perceived a significant higher discomfort than males at different body parts depending on the seat pitch conditions.

Table 8. Results of Mann-Whitney test (p-value ≤ 0.05).

	NECK	HEAD	RIGHT SHOULDER	LEFT SHOULDER	RIGHT ARM	LEFT ARM	RIGHT WRIST	LEFT WRIST	RIGHT HAND	LEFT HAND	UPPER BACK	MIDDLE BACK	LOW BACK	BUTTOCKS	THIGHS	KNEES	BEHIND KNEES	ANKLES	FEET
28 in	0.014	0.015	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.07	0.03	0.05					0.07		
30 in	0.022	0.018	0.07	0.04	0.04	0.05	0.06	0.06	0.07	0.07	0.01								
32 in		0.06																	

Both 28 in and 30 in seat pitch condition show significant differences in perceived discomfort at upper body areas: head, neck, arms, wrists, hands and upper back; middle back and behind the knees only for 28 inches. The 32 inches condition shows only one significant difference in perceived discomfort at head. The 28 inches seat condition show the highest number of significant gender-based differences in local perceived discomfort.

The results of Wilcoxon Signed Ranks test (Table 9) on the effect of sitting duration (T_2 vs T_0) highlight for the test conditions at 30 and 32 inches a significant increase over time of perceived discomfort at shoulders, arms (only for 32 inches seat pitch condition), hands (only for 30 inches condition), back, buttocks, thighs, only for 30 inches condition knees and ankles.

Table 9. Results of Wilcoxon signed rank test (p-value ≤ 0.05)

	NECK	HEAD	RIGHT SHOULDER	LEFT SHOULDER	RIGHT ARM	LEFT ARM	RIGHT WRIST	LEFT WRIST	RIGHT HAND	LEFT HAND	UPPER BACK	MIDDLE BACK	LOW BACK	BUTTOCKS	THIGHS	KNEES	BEHIND KNEES	ANKLES	FEET
28 in	0.06	0.01									0.05		0.08	0.07					
30 in			0.03	0.07					0.07	0.07		0.004	0.01	0.001	0.06		0.06	0.07	
32 in	0.03	0.04	0.01	0.01	0.02	0.05	0.05				0.05	0.02	0.07	0.06	0.07				

The mean pressure over time is comparable over the whole group and no significant correlation emerged between perceived discomfort per area and the pressure indices (mean and peak).

6.4 Discussion and Conclusions

The study focuses on the design and analysis of an experiment conducted in fuselage for the assessment of aircraft seating (dis-)comfort for different seat pitches involving a selected group of elderly potential passengers. The experiment was carefully designed to control the variability and to guarantee homogeneous test conditions.

The study explores the relationship between elderly passenger experience in different aircraft seat pitch that influences the legroom which is found to be a major element contributing to physical comfort of airline passengers.

The overall comfort score tended to be higher (in median) when the seat pitch enlarged from 28 inches to 32 inches. The small seat pitches (28 inches and 30 inches) restricted the subject leg movement, so that also their low back and buttocks had a high discomfort rating.

The overall comfort perceived at 28 inches is lower than the other two pitches analyzed, at both the beginning and the end of the test; whereas, at mid-test no significant difference in comfort emerged between the three seat pitches tested. However, in other similar situations with young potential passengers, comfort is not simply growing with a larger seat pitch, but there is a turning point where larger seat pitches lead to less well-being (Kremser et al., 2012).

The results about the gender-based differences in perceived discomfort reveal that elderly females perceived a significant higher discomfort than males at different body parts, depending on the seat pitch tested. The results obtained, for a seat pitch set at 32 inches, were compared with a previous study carried out in laboratory environment (Vanacore et al., 2019). The comparison showed that young male passengers (26-44 years old) involved in the laboratory study, perceived greater discomfort for the head and neck area, whereas the female elderly passengers perceived greater discomfort only for the head area. However, further investigation is necessary in order to understand how the pressure distribution varies with seat pitch and to relate these analyses with a study on passenger posture/movement.

Finally, results confirm that a reliable comfort assessment cannot be based on short-term evaluation since perceived discomfort increases significantly over time in several body areas. Indeed, it emerges that discomfort tends to increase for a greater number of body areas with a pitch of 30 inches and with a pitch of 32 inches; whereas with a seat pitch set at 28 inches, discomfort ratings are high from the first time of detection and for this reason fewer body areas are significant over time. Zhao et al. (2020), highlight that seat pitch has a significant impact on discomfort ratings, backrest and seat pan pressure variables after 1 hour sitting. Anjani et al. (2020), show with a group of young participants, the significant correlation between (dis-)comfort evaluations and seat pitch after 10 min of sitting, and highlight the need for long term studies to see the effect of time to (dis-)comfort.

In addition, it is interesting to note that, comparing the results with Vanacore et al. (2019), for similar test conditions, a significant increase over time of perceived discomfort turns out for more body areas than were found in the laboratory study with young passengers. Specifically, the body area resulted significant over time in terms of discomfort for elderly passengers are shoulders, back, sacrum and buttocks, already resulted in the laboratory study with young passengers (Vanacore et al., 2019), and all upper part of body, including hands and wrists.

The pressure analysis highlight there are different pattern of pressure distribution for each area (right and left buttock, right and left thigh) of seat pan, that means this implies the need to provide a differentiated pressure distribution that considers both the area of seat pan and the gender of the passenger. Further investigation is necessary, to investigate this result in a comparative framework, between young and elderly passengers, in order to understand whether an ideal distribution of pressures can also be proposed in aircraft area regardless of age.

The comfort, safety and functional independence of growing elderly passenger population might be improved with better aircraft seating design and a deeper understanding of the main factors influencing the comfort experience, widely investigated for young passengers and less so for elderly ones. The aim of this study was to investigate for a selected group of elderly passengers the relationship between seat pitch and (dis-)comfort and it has found a significant relationship between seat pitch and comfort as well as discomfort. An analysis was also done on the pressure distribution at 32 inches. It was a first fuselage study with elderly with an experimental setting to control the main noise factors on the evaluations, future research will be needed involving a group of young and old people evaluating both pressure distributions and postural movements for all tested conditions (seat pitches).

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CONCLUSIONS

It is now clear that offering a better travel experience to passengers in terms of comfort, for the same route, time and price, is an important factor for airlines to differentiate themselves in the market. At the same time, it is necessary to calibrate the services offered to take into account the changing passenger population with its different needs, especially due to the different age distribution.

The research work focused on the assessment of aircraft seat (dis-)comfort by subjective evaluations and objective data. A review about approaches proposed in the specialized literature for assessing the (dis-)comfort experience is provided in the thesis; however, the main corpus of the research work is devoted to providing a methodological framework for the assessment of passenger experience. The crucial point is the experimental design of laboratory/fuselage experiments and the proper data analysis of (dis-)comfort via a model-based approach.

The results highlight that correct experimental planning combined with appropriate data analysis make it possible to analyze the passenger (dis-)comfort experience in a simulated environment (i.e. laboratory and fuselage) and obtain diagnostic information on the strengths and weaknesses of the design solutions already in flight or in the certification phase. Since psychological and physiological biases generally affect the subjective assessment in a sample set, assessor's effect cannot be disregarded. Passengers of different ages simplified as young (under 60 years old) and elderly (over 60 years old) perceive the seat (dis-)comfort experience differently. For both groups (young and old) there is a time effect on the experience, i.e. as the sitting time increases, the perceived comfort decreases. A sufficiently long time should therefore be considered when conducting experimental campaigns for the assessment of seat (dis-)comfort. The comparison showed that young male passengers involved in the laboratory study perceived greater discomfort for the head and neck area, whereas the female elderly passengers perceived greater discomfort only for the head area.

Seat pitch has a significant influence on both groups of potential passengers involved in the experiment; both the young and the elderly tend to perceive worse the seat they are travelling on as the seat pitch tested decreases, so the results obtained by analyzing different seat designs are interesting and allow more legroom, as in the case of the Staggered seat hypothesized for the Flying V.

Finally, the choice of analysis methods that consider the real nature of the data collected made it possible to highlight, in the tested experimental conditions, significant relationships between overall perceived comfort and seat features as well as anthropometric characteristics of the sample.

Although a (dis-)comfort analysis is not necessary for the airworthiness certification of an airline seat, it is certainly useful to better qualify the seat. Therefore, the research sought to develop protocols and methods that would allow seat companies to perform reliable and easily interpretable comfort analyses, responding to a gap in the literature that showed a lack of “objective strategies” for proper comfort assessment.

Future Research

The analysis of objective data highlighted the need to develop increasingly sophisticated analysis protocols to account for the trend of these parameters over time by varying seats and passengers. We are conducting temporal analyses on these data, and we are introducing motion analysis for a more comprehensive seat comfort assessment. In the future we would like to include external noise factors, such as vibrations, to simulate the aviation environment even better. In addition, research should involve passengers, stratifying them not only by age and gender but also by geographical origin, and checking whether the psychological process of generating the subjective assessment also depends on their own culture.

APPENDIX A

Published papers:

1. Vanacore, A., Lanzotti, A., Percuoco, C., Capasso, A., Vitolo, B. (2019). Design and analysis of comparative experiments to assess the (dis-)comfort of aircraft seating. Applied ergonomics,76, 155-163.
2. Vanacore A., Percuoco C., The effect of noise factors in experimental studies on aircraft comfort, Contributo in Statistical Methods for Service Quality Evaluation Proceedings of IES 2019 Rome, July 4-5. BY PEARSON, Giugno 2020 ISBN 9788891921239.
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Design and analysis of comparative experiments to assess the (dis-)comfort of aircraft seating

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ABSTRACT

This paper focuses on the comparative assessment of comfort and discomfort (hereafter, (dis-)comfort) for aircraft seating. Subjective and objective data of seating (dis-)comfort were collected during an experiment involving 20 volunteers who tested 3 aircraft double-seats in upright and reclined position. In order to minimize experimental uncertainty due to well-known noise factors (*i.e.* patterns of discomfort during the work week and during the work day, order of evaluation, inter-individual differences), experimental trials were performed according to a crossover design. Statistical data analysis aimed mainly at investigating (dis-)comfort differences across seat conditions; gender-based differences in perceived discomfort on different body parts; effect of sitting duration on perceived discomfort on different body parts. The experimental results show that differences across seat conditions impacted differently on perceived discomfort depending on gender, body parts and sitting duration. No significant differences in perceived discomfort across gender were evident for the lightweight seat in both upright and reclined positions. On the contrary, for both baseline configurations, perceived discomfort at head and neck areas was higher for males than for females. For all seat conditions, participants experienced a significant worsening of perceived comfort over time at shoulders, back, sacrum and thighs and, in addition, at upper body area (*i.e.* neck, arm and forearm) and knees only for seats in reclined position.

1. Introduction

Over the last years, passenger air traffic has been constantly increasing and it grew impressively again in 2016, with 3.7 billion passengers carried by the world's airlines, supporting an increase in the passenger fleet of aircraft over 100 seats to over 19.000 aircraft, and also supporting record levels of deliveries from the manufacturers (Airbus, 2017–2036). For the next 20 years, the Airbus Global Market Forecast estimates a 4.4% global annual air traffic growth. Despite this growing demand, airlines are still one of the lowest-scoring industries in the American Customer Satisfaction Index (ACSI LLC, 2018).

Since the aircraft seat is rated as the most unsatisfying aspect of flying, sitting comfort improvement can provide a concrete opportunity for airlines to improve customer's satisfaction and loyalty and thus gain competitive edge in aircraft industry. Indeed, a high sense of comfort associated with a trip increases the proportion of passengers who wish to use the same aircraft on future occasions (Dolnicar et al., 2011; Vink, 2016).

The factors that affect the seat (dis-)comfort experience are many and heterogeneous. Following the theory of Helander and Zhang (1997), most of the models recently proposed in the specialized literature (*e.g.* De Looze et al., 2003; Hiemstra-van Mastrigt et al., 2017; Vink, 2016) conceptualize discomfort and comfort as two separate entities: discomfort is associated with feelings of pain, soreness, numbness and stiffness mainly attributed to physical constraints in the seat design; comfort is associated with feelings of relaxation and well-being. It is evident that reducing discomfort will not necessarily increase comfort, but in order to accomplish a high level of comfort, the level of discomfort should be low (Helander and Zhang, 1997).

Subjective characteristics (*e.g.* anthropometric variability, individual history and state of mind) make people experience different levels of (dis-)comfort in identical environments (Hiemistra-van Mastrigt, 2017; Lewis et al., 2016; Molenbroek et al., 2017; Vink, 2016; Smulders et al., 2016). Larger sized seats are rated more comfortable by taller occupants vice-versa shorter occupants rate smaller seats as more comfortable (Groenestejin et al., 2009; Vink, 2016); males and females are exposed to different loading patterns and experience different discomfort pathways, due to fundamental biomechanical differences in

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Table 1
Main anthropometric characteristics of the participants.

	Num.	Age [year] [min-max]	Weight [kg] [min-max]	Height [m] [min-max]	BMI [kg/m^2] [min-max]
Males	10	[24–42]	[69–100]	[1.60–1.90]	[22.4–34.4]
Mean (SD)		34.5 (6.04)	86.13 (10.10)	1.78 (0.07)	27.02 (3.46)
Females	10	[26–44]	[44.8–83.3]	[1.53–1.74]	[19.14–28.15]
Mean (SD)		33.7 (5.56)	67.2 (10.30)	1.66 (0.06)	24.3 (2.08)

their sitting posture (Dunk and Callaghan, 2005; Vos et al., 2006; Vink, 2016); Vink and Lips (2017) report significant differences between females and males in sensitivity to pressure stimuli at the seat pan and backrest of a vehicle seat. Differences on seating (dis-)comfort perception have also been investigated with respect to age (Kyung and Nussbaum, 2013).

Hiemstra-van Mastrigt et al. (2017) evidence that the relationship between human, seat and context characteristics and the perception of (dis-)comfort can be explained by three interconnected mediating factors: activity, posture and interface pressure.

Activity induces posture (Ellegast et al., 2012; Groenesteijn et al., 2012; Kamp et al., 2011), posture affects seat-interface pressure distribution (Vos et al., 2006; Tessendorf et al., 2009; Moes, 2007; Kyung and Nussbaum, 2013) which is the objective measure with clearest association with the subjective (dis-)comfort ratings (De Looze et al., 2003).

Another critical factor to consider when assessing (dis-)comfort is time in terms of both duration (*e.g.* flight length influences the state of mind of passengers; Vink, 2016) and timing (*e.g.* patterns of seat discomfort during the day and during the week; Bazley et al., 2015).

All the above factors and their interdependencies have to be recognized and accounted for in the evaluation of seating (dis-)comfort experiences.

This paper reports the design and the main results of an experiment for the comparative assessment of aircraft seating (dis-)comfort. The experiment aimed at gathering reliable information to diagnose seat design weaknesses and strengths and to provide useful suggestions for seat comfort improvement. It was carefully designed to minimize the impact of uncontrollable (*i.e.* noise) factors (*e.g.* timing, test order, inter-individual variability) and thus to guarantee repeatable and homogeneous test conditions.

The results of the experiment provide new insights on some relevant issues: the impact of anthropometric variability and sitting duration on aircraft seat (dis-)comfort, the correlation between overall perceived seat comfort and specific comfort features, the correlation between objective and subjective measures of (dis-)comfort, the identification of the female/male body parts which are more exposed to seating discomfort.

2. Materials and methods

The study involved a total of 28 subjects: a team of 8 experts (2 academics; 2 aircraft designers; 4 frequent flyers) who participated in the phase of development of the experimental protocol and a group of 20 volunteer participants (10 males, 10 females) involved in laboratory test sessions for the evaluation of the seating (dis-)comfort of 5 aircraft seat conditions.

Procedures for participant recruitment and data collection were defined taking into account ethical considerations. Before providing the informed consent, participants were fully informed on the type, number and duration of experimental sessions, as well as on the research aims and the treatment of the collected data.

2.1. Participants

Participants were required to be free from severe musculoskeletal disorders (MSDs) in the last year, to have taken at least one flight in the last two years and to be economy class flyers. In order to ascertain the above requirements, volunteers were asked to fill an informative questionnaire and a MSDs checklist so as to provide information on location, intensity and duration of any musculoskeletal injury experienced in the last year. These data were used only for participant selection purpose. The range, mean and standard deviation (SD) of the participant main anthropometric characteristics (*viz.* age, height, weight, and Body Mass Index-BMI) are reported in Table 1.

The sample is representative of anthropometric variability for both weight and height of the Italian adult population (Masali, 2013); only 1 participant was above the 99th percentile for weight and height. Furthermore, the mean values of BMI belong to the 95% credible intervals for BMI provided for the Italian population (NCD Risk Factor Collaboration, 2016).

2.2. Seats

Participants assessed the (dis-)comfort of 2 typical double-seats identified as “baseline configurations” (denoted seat A and seat B; Fig. 1) and 1 lightweight double-seat (denoted C; confidential) in upright and reclined position. The three double-seats under study have been designed for economy class regional aircraft market and differ from each other in terms of weight, reclining, headrest and dimensions of seat pan and backrest (Table 2). The seat bottom structure is in aluminium-alloy but only the bottom structure of seat C is optimized versus strength-to-weight ratio. Seat A and seat B share the same backrest configuration with frame in aluminium and sheet in carbon fiber assembled through metallic rivets (hybrid configuration); seat C backrest has a fully composite configuration made of carbon fiber reinforced polymer. The weight of seat C is about −8% compared to the “baseline configurations”.

Fig. 1. Seat A and seat B with Tekscan 5330 CONFORMat™.

Table 2
Seat dimensions.

	SEAT A	SEAT B	SEAT C
Cover (seat pan and backrest)	No differences in terms of materials and padding		
Seat padding	Same foams but different percentages		
Height of seat [mm]	1087	1152	1136.6
Height of seat pan [mm]	435	440	453.2
Depth of seat pan [mm]	432	452	471.3
Width of seat pan [mm]	424.9	424.9	457.2
Backrest configuration	hybrid	hybrid	full composite
Height of backrest[mm]	707	772	780
Width of backrest [mm]	427	450	444.5
Width of armrest [mm]	49.8	49.8	49.8
Reclining [mm]	no	yes (80)	yes (127)

Seat A, being not reclining, was tested only in upright position (*i.e.* seat condition: AU) while seat B and seat C were tested both in upright (*i.e.* seat conditions: BU, CU) and reclined position (*i.e.* seat conditions: BR, CR).

2.3. Objective measurements

Overall and local occupant-seat interface pressures were collected continuously during each test session, using two Tekscan (South Boston, MA, USA) pressure mats (5330 CONFORMat™), one for the seat pan and the other for the backrest (Fig. 1). Each pressure mat comprises 1024 (32 × 32) thin (1.78 mm) resistive sensors that could easily conform to the contour of the seat and measure up to 250 mmHg (5 PSI). Each mat has an active area of 471.4 mm × 471.4 mm and sensor pitch is 14.73 mm (0.5 sensor/cm^2). Pressures were recorded at a frequency of 50 Hz.

Before starting the experiment, the two pressure mats were calibrated according to the calibration procedure described in the user manual provided by Tekscan.

2.4. Subjective measurements

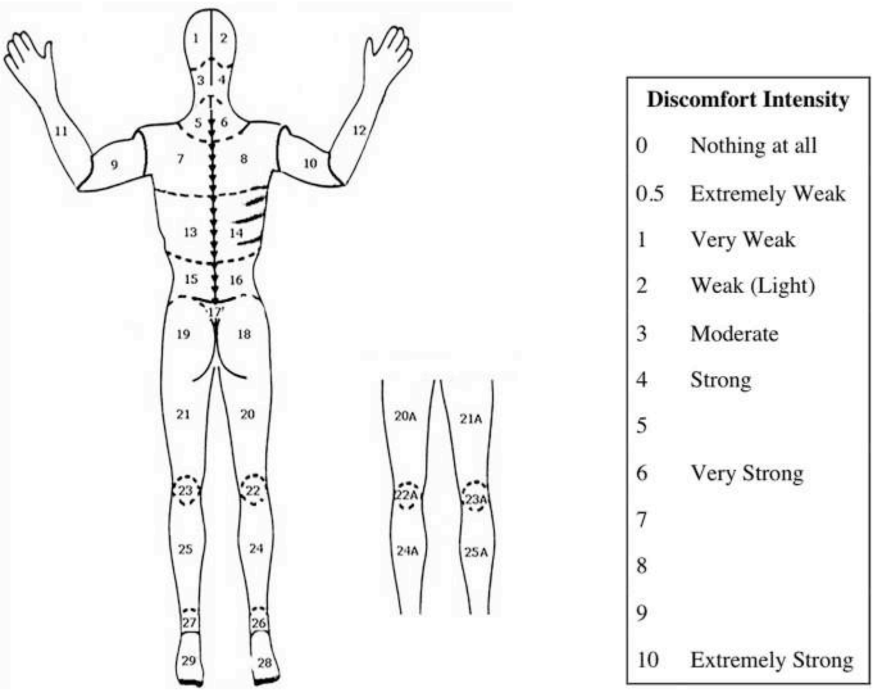
Subjective evaluations were collected by a trained interviewer who, at fixed time intervals, asked participants to express their perceptions about seating (dis-)comfort experience. Specifically, global and local discomfort perceptions were collected using a local discomfort map and a scale for perceived discomfort intensity (CR-10 scale; Borg, 1982). The map consists of 35 body parts (6 front, 29 back) as reported in Fig. 2; it was adapted from the body map proposed by Corlett et al. (1986) by adding four body parts (*i.e.* head, sacrum, knees and feet) and detailing the body parts for left/right and back/front side.

The CR-10 scale is recognized as a valid and reliable scale for evaluating seat discomfort (Shen and Parsons, 1998) and it is widely adopted in experimental studies on seating discomfort in combination with body maps.

Global and local comfort perceptions were collected using a Seating Comfort Form (SCF) consisting of 13 comfort statements (listed in Appendix A): the first 12 comfort statements addressing specific seat pan and backrest comfort statement (*e.g.* "The cushion padding is comfortable") were carefully chosen so as to differentiate the seats and to point out the critical features for passenger seat comfort improvement; the last comfort statement addresses the overall seat comfort (*i.e.* "The seat is comfortable"). Subjects were asked to assign to each statement a score between 0 and 10.

Before starting the experiment, the content validity of SCF was evaluated by the team of 8 experts adopting the Lawshe's method (Lawshe, 1975). Experts were asked to rate each comfort statement in the SCF as "essential", "useful" or "not necessary" to measure seating comfort; the responses from all experts were pooled and the number of responses "essential" for each statement was determined; Lawshe's content validity ratio (CVR) was calculated and compared against the associated critical threshold value (Ayre and Scally, 2014). The content validity of the 13 comfort statements was considered adequate being the values of CVR between 0.75 (*i.e.* 7 out of the 8 experts judged the statement as "essential") and 1.00 (*i.e.* 8 out of the 8 experts judged the statement as "essential").

The internal consistency and the reliability of the SCF were assessed during a pilot study involving the 20 participants in two test sessions each lasting 20 min. The pilot study was intended to test the experimental protocol as well as to familiarize the participants with it. Internal consistency was evaluated via Cronbach's α (Hayes, 2008) and



Discomfort Intensity	
0	Nothing at all
0.5	Extremely Weak
1	Very Weak
2	Weak (Light)
3	Moderate
4	Strong
5	
6	Very Strong
7	
8	
9	
10	Extremely Strong

Fig. 2. Body map and discomfort intensity scale.

provided a satisfactory result (*i.e.* $\alpha = 0.89$). SCF reliability was evaluated via inter-rater agreement and intra-rater agreement: the former refers to the agreement among evaluations provided by different raters; the latter refers to the agreement between evaluations provided by the same rater in two testing sessions (*i.e.* test-retest reliability). Both inter-rater agreement and intra-rater agreement were evaluated via the weighted Brennan-Prediger coefficient (Gwet, 2014; Vanacore and Pellegrino, 2017, 2018).

The values obtained for the inter-rater agreement coefficient were always higher than 0.7 meaning that, for each of the 13 comfort statements, the agreement among the participants was more than substantial. Moreover, more than 80% of participants provided ratings agreeing substantially or almost perfectly over the two test sessions (*i.e.* intra-rater agreement coefficient higher than 0.7).

2.5. Experimental protocol

In the laboratory environment, double-seats were placed in two rows and participants sat in the second row. Since the range for seat pitch in economy class is from 28 to 33 inches, a pitch of 32 inches was fixed in order to realistically replicate legroom.

Each test session lasted about 40 min. During each test session the participant performed the task of reading/playing a game with the smartphone.

Participants were asked to wear comfortable clothes, free of heavy seams and buttons, wallets and belts. During the test, each participant sat comfortably in a fixed posture with:

- feet flat on the floor so as to form a thigh-leg angle equal to 90°;
- back resting against the backrest;
- forearms not resting on the armrests;

Only 1 female participant (*i.e.* the 2.5th percentile for height) had problems with fixed posture since she was not able to reach the floor with feet flat to form a thigh-leg angle equal to 90°. For this specific case, we used a support platform for feet.

In each test run, pressure distribution was recorded continuously whereas subjective (dis-)comfort evaluations were collected at fixed time intervals. At the beginning (T0) and at the end (T2) of each test session, the trained interviewer asked the participant to rate each of the 13 comfort statements included in the SCF using a 11-point scale ranging from 0 (*i.e.* the participant does not agree at all with the statement) to 10 (*i.e.* the participant completely agrees with the statement); in the middle (T1) and at the end (T2) of each test session the interviewer provided the participant with a local discomfort map (Fig. 2) and asked her/him to indicate the body parts (i.e. 1, …, 20, 20A, …, 29) where she/he felt discomfort specifying for each of them (if any) the discomfort intensity level (Fig. 3).

2.6. Experimental plan

The test sessions were planned using a cross-over design (Jones and Kenward, 2014) taking into account three main noise factors: day of the week, time of the day and inter-individual variability which could impact on (dis-)comfort assessment (Table 3). Specifically, the 20 test sequences were defined using a 5 × 5 Greek Latin square with 4 replications and then assigned randomly to participants.

In order to avoid carry-over effects, a lower bound of 72 h for washout period was fixed between consecutive test sessions involving the same participant.

Fig. 3. Test set-up on "baseline configuration".

Table 3
Seat conditions and noise factors.

SEAT CONDITIONS	NOISE FACTORS		
	Days	Time slots	Inter-Individual Variability
AU	Monday	08:00–09:30	Participant (1, 2,., 20)
BU	Tuesday	09:30–11:00	
BR	Wednesday	11:00–12:30	
CU	Thursday	13:00–14:30	
CR	Friday	14:30–16:00	

3. Statistical data analysis

Statistical data analysis aimed at investigating:

- differences in perceived comfort among seat conditions;
- gender based differences in perceived local discomfort;
- effects of sitting duration on perceived local discomfort;
- occupant-seat interface pressure distributions;
- relationship between objective and subjective measures of overall and local (dis-)comfort.

Differences in perceived comfort among the 5 seat conditions were tested via Kruskall-Wallis test and Wilcoxon Matched-Pairs Signed Ranks test for post hoc pairwise comparisons with p value adjusted using Bonferroni's correction; the correlation between overall seat comfort and the comfort due to specific feature of each seat condition was investigated via Spearman's rank correlation coefficient.

Gender based differences in perceived local discomfort were tested via Mann Whitney test using the discomfort scores collected at T2. Effects of sitting duration on perceived discomfort were analysed via Wilcoxon Signed Ranks test on local discomfort scores collected at T0, T1 and T2.

The distribution of the occupant-seat interface pressure was analysed via the Load Comfort Loss (LCL) index based on differences between the observed load distribution and an ideal load distribution.

In order to investigate the relationship between objective and subjective measures of overall and local (dis-)comfort, the values of mean pressure, peak pressure and LCL, for seat pan and backrest, were correlated to 5 indicators of perceived (dis-)comfort: overall comfort; comfort with specific seat pan and backrest features (comfort statements from 1 to 4 and from 5 to 9, respectively); total discomfort at backrest; total discomfort at seat pan; total body discomfort. Total discomfort at backrest and total discomfort at seat pan were estimated by summing up discomfort scores provided for body parts in contact with the backrest (*i.e.* body parts 5–8 and 13–16) and the seat pan (*i.e.* body parts 17–23), respectively. Total body discomfort was obtained as the sum of total discomfort at backrest and total discomfort at seat pan.

All statistical tests were considered “significant” for p value ≤ 0.05.

Table 4
Spearman's rank correlation r_s (p value ≤ 0.05).

Seat Comfort Statements	AU	BU	BR	CU	CR
1. The cushion padding is comfortable.	0.580	0.544	0.884	0.750	0.781
2. The cushion fits comfortably under buttocks.	0.493	0.792	0.687	0.687	0.532
3. The cushion fits comfortably under thighs.		0.537		0.612	
4. The cushion fits comfortably behind knees.			0.755		
5. The backrest padding is comfortable.	0.887	0.814	0.654	0.774	0.630
6. The backrest fits comfortably at shoulders.	0.892	0.848		0.710	
7. The backrest fits comfortably at middle back.	0.909	0.830	0.768	0.611	0.690
8. The backrest fits comfortably at low back.	0.807	0.841	0.622	0.514	0.528
9. The lumbar support is comfortable.	0.769	0.854	0.792	0.646	0.618
10. The seat does not make you feel slipping down.	0.598	0.706			0.755
11. The seat does not make you feel forward thrusting.					0.592
12. The seat does not make you feel sinking into the cushion.			0.737		

3.1. *Comfort loss based on load distribution*

The Load Comfort Loss (LCL) here proposed is based on the relative Load (*rL*) over the contact surface between the human body and the seat. The LCL differs from other parameters used to synthetize information on pressure distribution (*e.g.* mean pressure, peak pressure, gradient, etc.; Hiemstra-van Mastrigt, 2017) in fact, being based on an ideal load distribution (Mergl, 2006), it accounts for differences in pressure sensitivity for areas of the human body in contact with the seat pan and backrest. The LCL weights the gaps between ideal load and observed load according to the representativeness of each subject inside the target population.

Let k be a generic occupant and let p_{ijtk} be the interface pressure recorded at time step t over cell ij of the sensor matrix, the relative Load is obtained as follows:

$$rL_{ijtk} = \frac{p_{ijtk} \cdot A_c}{L} \tag{1}$$

where A_c is the cell area (2.17 cm^2) and L is the total Load over the active cells.

Assuming a (Nominal the Best, NB) quadratic loss function and moving from the hypothesis that ideal pressure distribution leads to a high comfort rating (Vink, 2016), any deviation from this ideal (target) value can be interpreted as a comfort loss.

The comfort loss experienced over cell ij at time step t by occupant k is formulated as follows:

$$CL_{ijtk} = K(rL_{ijtk} - rL_{ij}^{*})^2 \tag{2}$$

where rL_{ij}^{*} is the ideal load assumed for the cell ij and K is a proportionality constant expressed as $K = C/\Delta^2$ being C the expected cost related to the maximum acceptable deviation Δ from the ideal load. Without loss of generality, C can be assumed unitary ($C = 1$). A reasonable estimate for Δ is the maximum deviation from rL_{ij}^{*}, observed for low perceived discomfort (*i.e.* intensity level ranging from 0 to 2 over the CR-10 scale shown in Fig. 2).

Starting from (Eq. (2)), the expected load comfort loss due to the difference between the observed load and the ideal load for cell ij can be derived for occupant k as follows:

$$LCL_{ijk} = K \cdot \left[\sum_{t=1}^{T} \frac{(rL_{ijtk} - \overline{rL}_{ij\bullet k})^2}{T-1} + (\overline{rL}_{ij\bullet k} - rL_{ij}^{*})^2 \right]; \overline{rL}_{ij\bullet k} = \frac{1}{T} \sum_{t=1}^{T} rL_{ijtk} \tag{3}$$

being $\overline{rL}_{ij\bullet k}$ the mean relative load over the total number of step times T.

The individual LCL in Eq. (3) can be evaluated for the whole seat, the seat pan, the backrest, or for specific areas of interest (*i.e.* left/right buttock, left/right thigh, upper/lower back) by simply summing it up over the related active cells. An estimate of the overall LCL can be obtained by averaging the individual LCL values obtained using Eq. (3) over the sample of occupants testing the seat.

4. Results

4.1. *Differences in perceived comfort among seat conditions*

No significant differences in perceived comfort among seat conditions were found by Kruskal Wallis test, except for the statement referring to the slipping down feeling (p value < 0.01). The post hoc analysis via Wilcoxon Matched-Pairs Signed Ranks test pointed out that seat B in reclined position (*i.e.* BR) obtained the worst evaluation for the slipping down feeling (BR vs AU, p value < 0.01; BR vs BU, p value < 0.01).

The results of Spearman's rank correlation (Table 4) highlight for all 5 seat conditions a positive correlation between overall comfort and 6 specific seat features (*i.e.* cushion padding, cushion fit under buttock area, backrest padding, backrest fit at middle back area, backrest fit at low back area and lumbar support). The correlation is generally higher for baseline seat conditions than for lightweight seat conditions. Specifically, both baseline configurations in upright positions (*i.e.* AU, BU) show a very strong correlation (*i.e.* $r_s > 0.80$) between overall comfort and comfort statements related to the backrest; vice-versa the overall comfort for the baseline seat in reclined position (*i.e.* BR) is very strongly correlated to the comfort of the cushion padding.

4.2. *Gender based differences in local perceived discomfort*

The results of Mann Whitney test for gender-based differences on local discomfort (Table 5) reveal that males perceived a significant higher discomfort than females at different body parts depending on the seat conditions. Both baseline seats show significant differences in perceived discomfort at upper body areas: head and neck for both seats; arm and forearm only for seat B. The baseline seat B shows the highest number of significant gender based differences in local perceived discomfort whereas no significant gender based differences in local discomfort result for the lightweight seat in upright position (*i.e.* CU).

4.3. *Effects of sitting duration on local perceived discomfort*

The results of Wilcoxon Signed Ranks test (Table 6) on the effect of sitting duration (T2 vs T0) highlight for all seat conditions a significant increase over time of perceived discomfort at shoulders, back, sacrum, buttocks and thighs; in addition, seats in reclined position (*i.e.* BR and CR) show a worsening in discomfort also at upper body parts (*i.e.* neck, arm and forearm) and knees.

4.4. *Occupant-seat interface pressure distributions*

The distributions of pressure at occupant-seat interface for each group (*i.e.* females and males) and each seat condition are graphically displayed via the maps of the mean peak pressure at backrest (Fig. 4) and seat pan (Fig. 5). Differences with respect to the assumed ideal load

Table 5
Results of Mann-Whitney test (*p value ≤ 0.05).

	Left						Right					
	Body part	AU	BU	CU	BR	CR	Body part	AU	BU	CU	BR	CR
Head	1	*	*		*		2	*	*		*	
Neck	3	*	*		*		4	*	*		*	
	5						6					
Shoulder	7						8					*
Arm	9				*		10				*	
Forearm	11		*		*		12		*			
Back	13						14					
	15						16					
Sacrum	17						17					
Buttock	19						18					
Thigh (back)	21		*		*		20				*	
Knee (back)	23		*		*	*	22				*	*
Low Leg (back)	25				*		24				*	
Ankle	27		*		*		26				*	
Foot	29						28				*	
Thigh (front)	21A		*				20A		*			
Knee (front)	23A		*				22A					
Leg (front)	25A				*	*	24A				*	*

distribution are summarized via LCL values (Table 7): the lightweight seat configuration shows the best results for LCL for both backrest and seat pan.

4.5. Relationship between objective and subjective measures of overall and local (dis-)comfort

The results of correlation analysis between subjective measures of overall and local (dis-)comfort and objective measures derived from occupant-seat interface pressure distribution (*i.e.* LCL, mean pressure and peak pressure) are reported in Table 8.

Correlation intensity is generally moderate. Strong correlation is found between: comfort evaluations for cushion fit behind knees and LCL; mean pressure and peak pressure measured at seat pan; comfort evaluations for backrest fit at shoulders and mean pressure at backrest; total body discomfort and peak pressure at backrest. LCL and mean pressure correlate to overall and local comfort measures but they show no significant correlation with discomfort measures; vice-versa, peak pressure correlates significantly also to overall and local discomfort measures. It is worthy to note that, differently from LCL, mean pressure and peak pressure show significant correlations only locally (*i.e.* at backrest and seat pan).

5. Discussion

This paper focuses on the design and analysis of a laboratory experiment for the comparative assessment of aircraft seating (dis-)comfort.

The experiment was carefully designed to force variability to occurr and meanwhile guarantee homogeneous test conditions (i.e. with respect to activity, posture and state of mind of involved participants).

In order to simulate anthropometric variability, participants were selected so as to obtain a balanced and representative sample of Italian adult population (in the range from 24 to 44 years).

The effect of activity and body posture was controlled by assigning the same activity and imposed posture to the participants during the experiment. The activity of reading/playing a game with the smartphone is one of the most frequently performed by passengers during public transport and semi-public situations (Hiemstra-van Mastrigt et al., 2016; Kamp et al., 2011); moreover, it is classified as a high level activity in which the trunk is mostly straight against the backrest (Hiemstra-van Mastrigt et al., 2017) and thus it allows to collect

Table 6
Results of Wilcoxon test (*p value ≤ 0.05).

	Left						Right					
	Body part	AU	BU	CU	BR	CR	Body part	AU	BU	CU	BR	CR
Head	1			*			2			*		
Neck	3			*	*	*	4			*	*	*
	5		*	*	*	*	6		*		*	*
Shoulder	7	*	*	*	*	*	8	*	*		*	*
Arm	9				*	*	10			*	*	*
Forearm	11	*				*	12	*			*	*
Back	13	*	*	*	*	*	14	*	*	*	*	*
	15	*	*	*	*	*	16	*	*	*	*	*
Sacrum	17	*	*	*	*	*	17	*	*	*	*	*
Buttock	19	*	*	*	*	*	18	*	*	*	*	*
Thigh (back)	21	*	*	*	*	*	20	*	*	*	*	
Knee (back)	23	*			*	*	22	*			*	*
Low Leg (back)	25		*	*	*		24			*	*	
Ankle	27			*	*	*	26			*	*	*
Foot	29			*	*	*	28			*	*	
Thigh (front)	21A	*	*	*	*	*	20A	*	*	*	*	*
Knee (front)	23A		*	*	*		22A				*	
Leg (front)	25A			*	*	*	24A		*	*	*	*

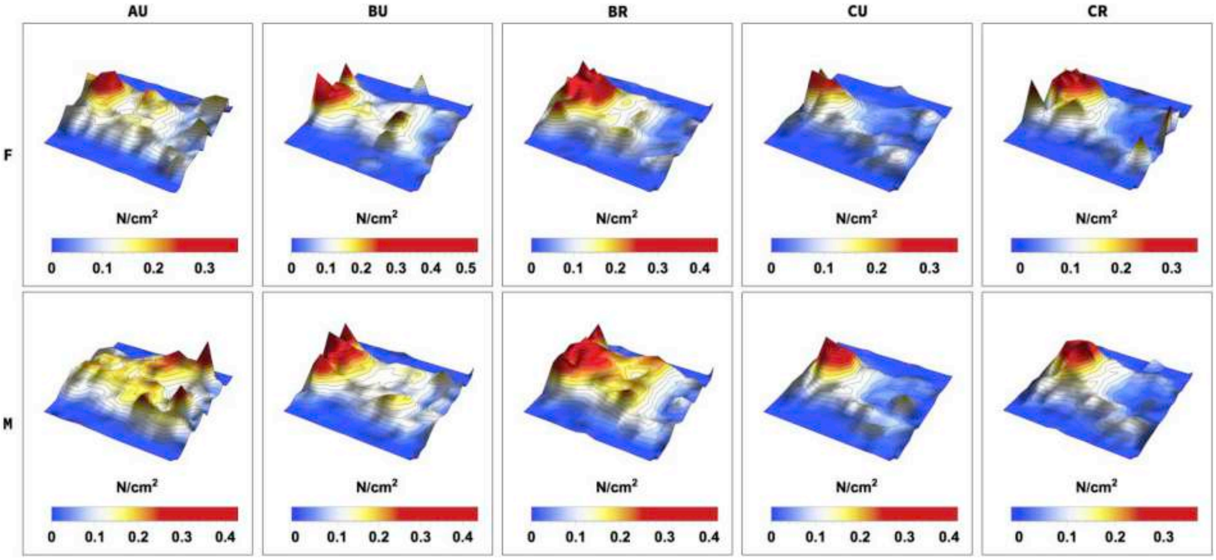


Fig. 4. Maps of the mean Peak Pressure at backrest stratified by gender and seat conditions.

pressure data also over back area.

The passenger state of mind is too complex to be simulated or controlled during a laboratory experiment. Some studies show that it is significantly influenced by passenger expectations about time in terms of both duration (*e.g.* flight length; Vink et al., 2012) and timing (*e.g.* day of the week and time of the day; Bazley et al., 2015). We fixed the test session length at 40 min; under the condition of imposed activity and posture, a longer test session would have induced feelings of fatigue and boredom which bias the assessment of seating (dis-)comfort with respect to seat characteristics.

Literature studies that investigate the effects of time on seating discomfort during longer sessions do not impose posture or plan some break (*e.g.* Hiemstra-van Mastrigt et al., 2016; Smulders et al., 2016). In Hiemstra-van Mastrigt et al. (2016) the duration of each sitting session was 1.5 h, however in each session participant simulated 4 distinct activities (i.e. upright sitting for 'take-off', eating and drinking, reading an inflight magazine, and sleeping or relaxing in reclined position) each lasting 15, 15, 30 and 30 min, respectively.

During each test session global and local comfort perceptions were collected using a novel Seating Comfort Form (SCF), whose validity was tested before starting the experiments in terms of content validity, internal consistency and reliability.

Global and local discomfort perceptions were collected using a body map and CR-10 scale, both tools are universally practiced in field literature. In order to carefully localize discomfort areas, a detailed map — differentiating left/right and back/front side body parts — was used. During the pilot study aimed at testing the experimental protocol, neither pitfalls in using the detailed body map nor claims on acceptability emerged. The higher level of details allows participants to better locate and differentiate discomfort areas without increasing the level of complexity for data collection since the experimental protocol required that participants indicated only the body parts where they experienced a non-null discomfort intensity level. Moreover, as resulted from

Table 7
Load Comfort Loss (LCL) at backrest and seat pan.

	AU	BU	BR	CU	CR
Backrest	1.021	1.060	1.025	0.983	0.960
Seat pan	1.097	1.097	1.153	1.012	1.013

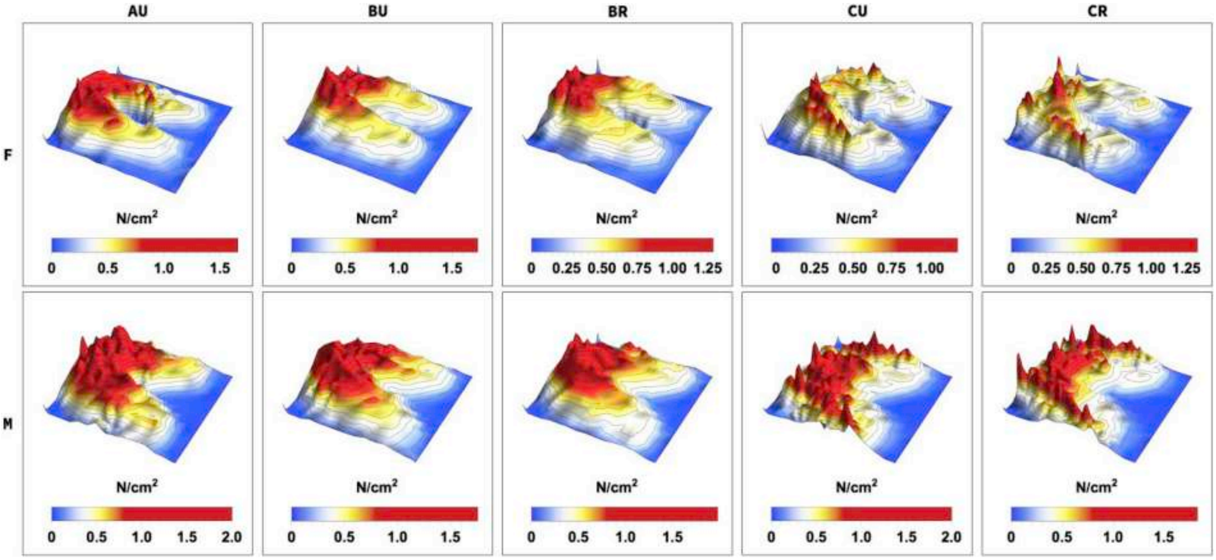


Fig. 5. Maps of the mean Peak Pressure at seat pan stratified by gender and seat conditions.

Table 8
Spearman's correlation (r_s) between objective and subjective measures of (dis-)comfort stratified by seat conditions (p value ≤ 0.05).

Objective measures of (dis-)comfort	Subjective measures of (dis-)comfort	AU	BU	CU	BR	CR
LCL over the seat	Overall Comfort		−0.473			
LCL at backrest	Backrest fit at middle back		−0.463			
	Overall Comfort		−0.467			
LCL at seat pan	Cushion fit behind knees		−0.561	−0.688		−0.530
Mean pressure at backrest	Backrest padding					0.508
	Backrest fit at shoulders					0.637
	Backrest fit at low back					0.509
	Lumbar support	0.519			0.487	
	Overall Comfort				0.482	
Mean pressure at seat pan	Cushion fit behind knees	−0.615		−0.672	−0.641	−0.659
Peak pressure at backrest	Lumbar support				0.478	
	Total Discomfort at backrest					−0.553
	Total Body Discomfort					−0.671
Peak pressure at seat pan	Cushion fit at buttocks				−0.508	
	Cushion fit behind knees			−0.757		
	Total Body Discomfort				0.515	

statistical data analysis, detailing the body parts with respect to left/right and back/front side allowed to discover laterality in discomfort perception: statistical evidences for discomfort at thigh, knees and ankle refer only to the left side.

The statistical analysis of discomfort data provided statistical evidence of differences in local discomfort perceptions between males and females. Studies conducted in both office chairs and automobile seats have mainly investigate differences in sitting postures across gender: findings reveal that men tended to slouch against the back rest while females perched closer to the front of the seat pan; (Dunk and Callaghan, 2005; Callaghan et al., 2010). Recent research studies have put the attention on local discomfort differences across gender. In particular, Vink and Lips (2017), using a dose-response approach in laboratory environment, identified differences in pressure sensitivity for areas of the human body in contact with the seat pan and backrest of a vehicle seat.

To the best of our knowledge, gender-based differences in local discomfort have not been taken into account when examining different configurations of aircraft seats. The results of our study provide statistical evidences that males perceived more discomfort at the head and neck areas for seats A and B, behind knees and at low legs for seat B and C. The design of seat C resulted the most robust with respect to gender differences.

As regards the effect of exposure duration, overall discomfort significantly increased over time for all seats under study with positive trend starting after 15 min: for seats configurations in upright position, perceived discomfort increased significantly at shoulders, back, sacrum and thighs; whereas for seats configuration in reclined position, the increase in perceived discomfort was significant at neck, arm, forearm and knees.

The statistical evidences provided in our study confirm the tendency observed in other studies which demonstrated the effect of sitting duration over perceived discomfort (*e.g.* Hiemstra-Van Mastrigt et al., 2016; Smulders et al., 2016; Jackson et al., 2009; Na et al., 2005; Noro et al., 2005; Porter et al., 2003).

The correlation between pressure variables and passenger perceived (dis-)comfort has been investigated in many studies, but because of large differences in measurement and analysis of the different pressure variables, the strength of this correlation is not clear and make it difficult to conclude whether or not pressure variables are related to comfort and/or discomfort (Zemp et al., 2015).

In our study, the correlation analysis between objective and subjective measures of (dis-)comfort shows that peak pressure and mean pressure value are not uniquely and easily interpretable. Peak pressure correlated to both perceived discomfort and perceived comfort. The mean pressure at back resulted positively correlated to the comfort of backrest characteristics: the higher the mean pressure over back area, the higher the comfort ratings for backrest characteristics and vice-versa. On the other hand, the mean pressure behind the knees resulted negatively correlated to perceived discomfort at. Therefore, it is recommended to interpret the values of mean pressure taking into account differences in pressure sensitivity over different body areas. Correlation results for LCL index resulted more clearly interpretable. Overall LCL resulted significantly correlated with overall comfort evaluation. Since LCL measures the comfort loss with respect to an ideal pressure distribution, it is logical to expect that the correlation between LCL and perceived comfort measures was negative, as emerged from the results of our analyses.

6. Conclusion

The strategy for comparative (dis-)comfort assessment (i.e. experimental design, material and method, statistical data analysis) proposed in this paper produced statistical evidences that could be usefully exploited in future research to identify a predictive model of passenger (dis-)comfort which was beyond the aims of this paper.

The results of the (dis-)comfort assessment highlight that the lightweight seat has a higher level of comfort when compared to the two tested baseline configurations. This result is in line with findings obtained in other studies which demonstrated that the comfort of lightweight seats can be kept at the same level as a basic seat configuration and can even be improved if new technologies, designs and materials are used (Vink et al., 2012).

The results of this study can only be applied to the sampled population: young, healthy and active people without any history of low back pain. Several variables may alter (dis-)comfort response to sitting exposure such as age, somatotype, fitness and history of back pain. Moreover, participants expressed their evaluations under constrained test conditions (i.e. fixed posture and activity), future research will also further investigate the relationship between aircraft seating (dis-)comfort and changes in posture through the analysis of micro-movements.

Appendix A. List of seating comfort statements included in the seating comfort form (SCF)

1. The cushion padding is comfortable.
2. The cushion fits comfortably under buttocks.
3. The cushion fits comfortably under thighs.
4. The cushion fits comfortably behind knees.
5. The backrest padding is comfortable.
6. The backrest fits comfortably at shoulders.
7. The backrest fits comfortably at middle back.
8. The backrest fits comfortably at low back.
9. The lumbar support is comfortable.

10. The seat does not make you feel slipping down.
11. The seat does not make you feel forward thrusting.
12. The seat does not make you feel sinking into the cushion.
13. The seat is comfortable.

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The effect of noise factors in experimental studies on aircraft comfort

L'effetto dei fattori di disturbo sulla valutazione sperimentale del comfort aereo

Amalia Vanacore[1] and Chiara Percuoco[1]

Abstract This paper describes a strategy adopted for the analysis of aircraft seat comfort data collected in laboratory experiments. A crossover study was planned to investigate whether the noise factors related to inter-individual variability and timing impact on seating comfort perceptions. The data analysis strategy is based on cumulative link mixed models (CLMMs). The results confirm the necessity to control the noise factors in order to obtain a diagnostic assessment.

Abstract *In questo lavoro è descritta una strategia per l'analisi delle valutazioni sul comfort dei sedili aerei raccolte mediante esperimenti in laboratorio È stato pianificato uno studio di tipo crossover per indagare se i fattori di disturbo, ovvero la variabilità dei passeggeri e il tempo, influenzano la percezione del comfort di seduta aereo. La strategia di analisi proposta si basa sui cumulative link mixed models (CLMM). I risultati confermano la necessità di controllare i fattori di disturbo al fine di ottenere una valutazione diagnostica del comfort.*

Key words: seat comfort assessment, crossover design, cumulative link mixed models

1 Introduction

Commercial aviation is the most global of businesses: it is a growth market with more than 60% growth over the last ten years. Since 1990, both aircraft movements and the number of destinations have doubled. For the next 20 years, Airbus GMF [4]

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forecasts a 4.4% global annual air traffic growth. Despite this impressive growing demand, airlines are still one of the lowest-scoring industries in the American Customer Satisfaction Index [1] with the aircraft seat rated as the most unsatisfying aspect of flying. In this context, the improvement of aircraft seat comfort can provide a concrete opportunity for airlines to improve passenger satisfaction and loyalty and thus gain competitive edge in aircraft industry [15].

Experimental studies are the easiest way to learn more about comfort experience and collect diagnostic information to be used for improving product design.

Generally, laboratory experiments for comfort studies [8, 12, 15, 16] involve potential users (*i.e.* participants) to compare different products (*e.g.* aircraft seats and/or cabin interiors) in a simulated environment (*e.g.* equipped room or fuselage). The main advantages of laboratory experiments, compared to survey studies, are that the experimenters can control the environment under which the participants make their evaluations, and moreover, they allow to learn more about comfort experience with a significant reduction in costs and time for data collection [13, 14].

On the other hand, comfort data collected in laboratory experiments may be affected by two well-known noise factors: inter-individual variability and time. The inter-individual variability (*e.g.* anthropometric characteristics, individual history and state of mind) make participants experience different levels of comfort (or discomfort) in identical environments [9, 16]; time may impact on comfort evaluations not only in terms of exposure duration (*i.e.* experiment length) but also in terms of timing, indeed different patterns of discomfort may be experienced by the participants in different days of the week.

In order to characterize and quantify the effects of the above noise factors on the evaluations about aircraft seat comfort, a laboratory experiment was conducted involving a selected group of aircraft passengers. The experimental trials were planned according to a crossover design: each participant evaluated different aircraft seats with the aim of comparing them on a within-subject basis rather than on the group level [10]. Since comfort evaluations could not be assumed independent, collected data were analysed via a cumulative link mixed model (CLMM) [2, 3, 6].

The paper is organised as follows: in Section 2, an overview of the experiment is provided; the data analysis strategy is introduced in Sections 3; the experimental results are reported and discussed in Section 4; finally, conclusions are summarized in Section 5.

2 Overview of experiment

A total of 17 volunteers (8 females and 9 males; aged between 24 and 44 years) were selected to participate in the aircraft seat comfort experiment using the following criteria:

1. to be free from severe musculoskeletal disorders in the last year;
2. to have taken at least 2 flights in the last year;
3. to be economy class flyers.

Procedures for participant recruitment and data collection were defined taking into account ethical considerations. Before providing the informed consent, participants (hereafter, assessors) were briefed about the type, the number and the duration (40 minutes) of each comfort trial, as well as on the research aims and the treatment of the collected data. The selected group of assessors was representative of the anthropometric variability in the Italian adult population with respect to both weight and height (Table 1).

Table 1. Main anthropometric characteristics of the participants

	Num.	***Age [year] [min-max]***	***Weight [kg] [min-max]***	***Height [m] [min-max]***	***BMI [kg/m^2] [min-max]***
Males	9	[27.0-41.0]	[73.1-101.8]	[1.60-1.90]	[22.8-34.7]
Mean (SD)		34.6 (4.25)	88 (8.53)	1.77 (0.08)	28.03 (3.46)
Females	8	[26-44]	[55.5-75]	[1.55-1.73]	[21.2-27.5]
Mean (SD)		33.9 (5.9)	66 (5.41)	1.66 (0.05)	24.1 (2.08)

The comfort experiments took place in a laboratory environment equipped with two rows of double-seats for regional aircrafts. The assessors sat in the second row with a pitch fixed on 32 inches in order to realistically replicate legroom.

Each assessor evaluated, in different order, the comfort of 3 typical seats (hereafter identified as A, B and C). The seats A and B were baseline configurations whereas seat C was a lightweight seat. The three seats differed from each other in terms of weight, reclining, headrest and dimensions of seat pan and backrest. All the seats were designed for economy class regional aircraft market. Each assessor tested the 3 seats following a crossover design [10] built to investigate 3 main noise factors: the day of the week, the order of testing and the inter-individual variability.

Specifically, 18 test sequences were defined using a 3×3 Greek Latin square with 6 replications; the test sequences were randomly assigned to the assessors. The design was uniform within sequences and periods. Since only 17 assessors entered the comfort experiment, there was a slight imbalance in the crossover [11].

In order to avoid the sensory biases caused by the residual sensations of previously tested seat (*i.e.* carryover effects) a wash-out period of 72 hours was fixed.

In each comfort trial, a trained interviewer asked the assessor to rate the overall comfort perception with the seat as well as the comfort perception related to specific attributes of the seat pan (*i.e.* padding and comfort) and the backrest (*i.e.* padding and support).

3 Data analysis strategy

The analysis of data obtained from the aircraft seat comfort experiment aimed at explaining the variation in subjective responses in terms of treatments (*i.e.* seats), periods (*i.e.* days of the week) and testing order.

Comfort responses collected from the same assessor (*i.e.* replications or repeated measures) are likely to be more similar on average than responses provided by different assessors, thus they cannot be assumed independent.

Cumulative link mixed models (CLMMs) are a powerful and flexible approach to handling replicated ordinal responses [6]. The main features of this approach will be briefly described in the following.

Let y_{is} denote the response provided by subject i for object s; let $x_{1is},\ldots, x_{kis}$ denote the values of the k explanatory variables and let u_i be the random effect for subject i. For response categories $j = 1, 2, \ldots, c-1$, the cumulative logit model with a random intercept is

$$\operatorname{logit}\left[P\left(Y_{is} \leq j\right)\right] = u_i + \alpha_j - \beta_1 x_{1is} - \ldots - \beta_k x_{kis} \qquad (0)$$

The model in (0) takes the linear predictor from the marginal model and adds a random effect u_i to the cut-point term α_j. It uses the same random effect for each cumulative probability. Using an overall intercept term of form $u_i + \alpha_j$, the CLMM allows the ordinal scale cut-points to vary across subjects and thus it is a way of accounting for subjectivity in evaluations.

The random effect u_i is unobserved, so its value is unknown. It is usually assumed to vary from subject to subject according to a normal N $(0, \sigma_u^2)$ distribution. The variance component σ_u^2 is estimated together with the fixed effects [2, 3].

Likelihood ratio (LR) tests can be used to test fixed-effects model terms in the same way for cumulative link mixed models as in cumulative link models. A LR test of the random-effect term is a bit more complicated. Being the random effect standard deviation non-negative, the test is one-sided. The usual asymptotic theory for the LR statistic dictates that the LR asymptotically follows a χ^2 distribution with one degree of freedom. However, since the σ_u is on the boundary of the parameter space, the usual asymptotic theory does not hold. The LR more closely follows an equal mixture of χ^2-distributions with zero degrees of freedom (a point mass distribution) and one degree of freedom.

For this reason, it is often argued that a more correct interpretation is obtained from the adjusted p-value obtained by halving the p-value produced by the conventional LR test. Wald tests of the variance parameter can also be constructed, but since the profile log-likelihood function is only approximately quadratic, when σ_u^2 is not small and well defined, such tests cannot be recommended [6].

4 Results

Assuming the seat, the period and the testing order as fixed effects and the assessor as a random effect, the CLMM was fitted on the collected comfort responses (i.e overall seat comfort, seat-pan padding, seat-pan comfort, backrest padding and backrest support) using the ordinal package available in R [7].

For each fitted model, the estimates of the cut-point terms αj ($j = 1, 2$), the fixed effect parameters and their asymptotic standard errors are listed in Table 2 together with the p values obtained for Wald test and LR test.

Table 2. Cumulative logit mixed model fitted to aircraft seat comfort data

		Estimate	***St. error***	***Wald test p-value***	***LR test p-value***
Overall Comfort	α_1	-4.03	1.13		
	α_2	-1.63	0.90		
	Seat B	-1.25	0.95	0.18	**0.02**
	Seat C	-2.82	1.20	**0.01**	
	Order 2	0.90	0.99	0.36	0.26
	Order 3	1.73	1.14	0.13	
	Period 2	0.59	1.03	0.56	0.72
	Period 3	-0.18	0.74	0.80	
Seat-pan padding	α_1	-2.19	1.05		
	α_2	2.83	0.74		
	Seat B	0.54	0.78	0.49	0.80
	Seat C	0.26	0.88	0.76	
	Order 2	-0.53	0.89	0.55	0.38
	Order 3	0.61	0.92	0.50	
	Period 2	-0.14	1.03	0.88	0.78
	Period 3	0.26	0.88	0.48	
Backrest padding	α_1	-1.37	0.78		
	α_2	1.32	0.78		
	Seat B	0.57	0.69	0.40	0.26
	Seat C	-0.69	0.77	0.36	
	Order 2	-0.13	0.77	0.86	0.73
	Order 3	0.41	0.77	0.60	
	Period 2	-0.03	0.85	0.96	0.39
	Period 3	-0.82	0.66	0.21	
Backrest support	α_1	-0.61	0.85		
	α_2	2.08	0.94		
	Seat B	0.20	0.74	0.78	0.46
	Seat C	-0.81	0.83	0.32	
	Order 2	-0.78	0.86	0.57	0.60
	Order 3	0.27	0.82	0.74	
	Period 2	-0.47	0.97	0.62	0.79
	Period 3	-0.46	0.71	0.51	
Seat-pan comfort	α_1	-1.23	0.75		
	α_2	1.65	0.78		
	Seat B	-0.18	0.64	0.79	0.96
	Seat C	-0.16	0.77	0.83	
	Order 2	-1.48	0.82	**0.07**	**0.09**
	Order 3	-0.37	0.78	0.63	
	Period 2	0.05	0.86	0.95	0.93
	Period 3	-0.18	0.64	0.76	

The results in Table 2 highlight that the probability of obtaining a low rating for the overall comfort is significantly higher for seat C than for seats A and B ($\beta_{seatC} = -2.82$; *p-value* 0.02); under no circumstances the period (*i.e.* the day of the week) impacts significantly on comfort assessments, on the contrary the testing order impacts significantly on seat pan comfort evaluations ($\beta_{order} = -1.48$; *p-value* 0.09).

The estimates of the variance of the random effect reported in Table 3 suggest that the assessor effect is negligible for the responses about overall seat comfort; the same conclusion does not hold for the specific seat comfort attributes, since the results reflect a significant within-subject correlation for backrest support and seat pan padding and a slight correlation for backrest padding and the seat pan comfort.

Table 3. Estimated variance of assessor effect and p-values of LR tests

Comfort attribute	$\hat{\sigma}_u^2$	***LR test p-value***	***LR test adjusted p-value***
Overall comfort	<0.0001	1	0.5
Backrest padding	0.98	0.16	0.08
Backrest support	2.20	0.03	0.015
Seat-pan padding	5.56	0.0005	0.00025
Seat-pan comfort	0.26	0.63	0.32

The results of the LR test in Table 3 show that the assessor effect is significant in all models except for the overall comfort and the seat pan comfort.

The assessor effects, u_i, are not parameters, so they cannot be estimated in the standard way, but a "*best guess*" is provided by the conditional modes. Similarly the conditional variance provides an uncertainty measure of the conditional modes.

The assessor effects given by conditional modes with 95% confidence intervals based on conditional variance are plotted in Figure 1 and Figure 2 for specific comfort attributes related to the seat pan and the backrest, respectively.

Assessors #2 and #17 provided the lowest comfort ratings, whereas Assessors #1 and #16 generally gave the highest comfort ratings. The significant assessor effect indicates that assessors perceived the seat comfort differently. Two natural interpretations are that either the same comfort rating means different things to different assessors, or the assessors actually perceived the seat comfort differently. Possibly both effects play their part.

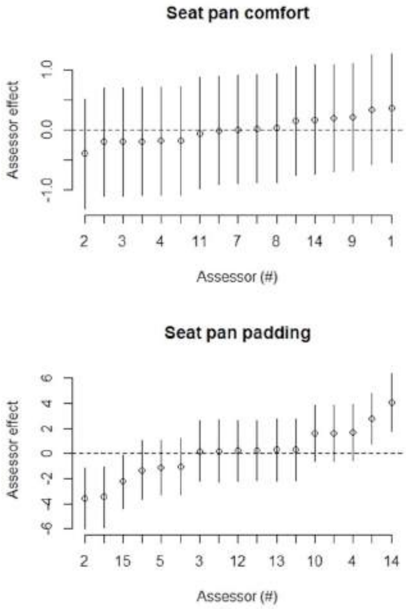

Figure 1. Assessor effect on seat pan attributes given by conditional modes with 95% confidence intervals based on the conditional variance

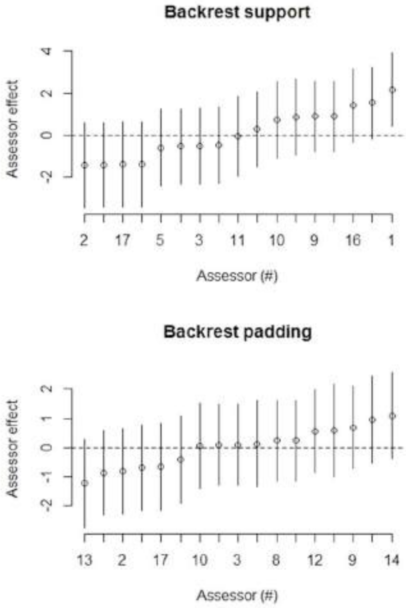

Figure 2. Assessor effect on backrest attributes given by conditional modes with 95% confidence intervals based on the conditional variance

5 Conclusions

The results of our study confirm that comfort experiments involving human assessors are prone to sensory biases due to experimental conditions and inter-individual variability. Well-designed experiments and proper data analysis strategies are thus required in order to obtain reliable information to be used for comfort improvement.

A well-designed experiment allows to control the main noise factors (*e.g.* period and testing order) causing sensory biases; on the other hand, a proper data analysis strategy allows to account for realistic violations of classical assumptions (*i.e.* normality and independence).

The results highlight that the assessor effect resulted negligible for the overall comfort and the seat pan comfort but it necessary to take this effect into account when dealing with subjective comfort perceptions related to specific seat features (*i.e.* seat pan padding, backrest support and backrest padding).

However, since psychological and physiological biases generally affect the subjective assessment in a sample set, assessor effect cannot be disregarded *a priori*.

Further investigations are necessary in order to check the generalizability of our findings outside the laboratory setting.

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A model-based approach for the analysis of aircraft seating comfort

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Abstract.
BACKGROUND: Aircraft seating comfort has a significant impact on passenger on-board experience. Its assessment requires the adoption of well-designed strategies for data collection as well as appropriate data analysis methods in order to obtain accurate and reliable results.
OBJECTIVE: This paper focuses on the assessment of aircraft seating comfort based on subjective comfort responses collected during laboratory experiments and taking into account seat features and passenger characteristics.
METHODS: The subjective comfort evaluations have been analyzed using a model-based approach to investigate the relationship between overall seating comfort and specific seat/user characteristics.
RESULTS: The results show that the overall seating comfort perception is significantly influenced by the thickness of the seat pan, the backrest position (upright or reclined), the age of the passenger and the passenger perception of being comfortably supported at the lumbar region.
CONCLUSIONS: The adopted model-based approach allows the analysis of subjective seating comfort data taking into account their ordinal nature as well as the dependency between evaluations provided by the same subject.

Keywords: Seat comfort, laboratory experiments, ordinal regression, repeated evaluations

1. Introduction

In the last decades, commercial air traffic and number of passengers have been constantly increasing and the competition among airlines has intensified, resulting in airlines seeking ways to differentiate their products and services and employing market penetration strategies based on price, point-to-point connections, timeliness, flight frequency and service quality [1–3].

Being strictly related to passenger satisfaction and willingness to pay, the improvement of on-board comfort has become a strategic goal for the airline management [4].

Literature studies highlight that passenger comfort experience mainly depends on *sitting comfort* [*e.g.* 5–9] and that, to attract passengers, seats should take into account the diversity of passengers (*e.g.* anthropometry, state of mind and expectations) and the activities they want to perform during travel [10, 11].

In recent years the number of papers touching comfort knowledge continues to expand, but the theoretical foundations for comfort research remain underdeveloped [12]. Several theoretical models have been proposed to explain and describe (dis-)comfort [*e.g.* 11, 13–15], but none of these models is able to predict either comfort or discomfort.

A recent literature review [16] evidences the necessity of more research to enable a better prediction, especially in the field of passenger seat (dis-)comfort (as opposed to driver's (dis-)comfort). The main factors related to sitting (dis-)comfort (*i.e.* human, context and seat characteristics) have only been

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considered in separate studies and the relationships between them and passenger (dis-)comfort remain unclear due to a lack of statistical evidence and large differences in research set-ups.

In this study, the focus is on comfort data collected during a laboratory experiment planned to explore the effects of seat design parameters and passenger characteristics on overall perceived comfort.

The data have been modeled using a cumulative link mixed model (CLMM) that is an extension of linear mixed models for ordinal data. The higher computational complexity of the adopted CLMM is counterbalanced by its higher flexibility that accounts for both the ordinal nature of the comfort evaluations and the dependency between evaluations provided by the same subject [17, 18].

2. Overview of the experiment

The experiment involved 17 frequent flyers (Table 1) with no history of back problems. Each participant was involved in 5 seating test sessions. Ethics approval was arranged and participants signed an informed consent.

Participants assessed the comfort of 2 typical double-seats identified as "baseline configurations" (denoted seat A and seat B) and 1 lightweight double-seat (denoted C; confidential). The three double-seats under study differ in weight, reclining, headrest and dimensions of seat pan and backrest (Table 2).

Seat A, being not reclining, was tested only in upright position while seat B and seat C were tested both in upright and reclined position.

The test sessions were planned using a cross-over design [19] and were carried out following a detailed experimental protocol. At the end of each test session, lasting about 40 minutes, with fixed posture and task (reading/playing a game with the smartphone), the participant evaluated the comfort of specific seat features using a scale with three ordered categories (*i.e.* 1: low comfort, 2: medium comfort, 3: high comfort) and scored the overall seating experience using an ordinal scale ranging from 0 (*i.e.* no comfort) to 8 (*i.e.* extreme comfort).

3. Methods

Comfort ratings have been analyzed in a regression setting using a set of covariates representing: 1) objective seat features (*viz.* height of seat, height of seat pan, width of seat, backrest configuration, height of backrest, thick of backrest, backrest reclining); 2) participant anthropometrical characteristics (*viz.* gender, age and BMI); 3) participant feelings of comfort with specific seat features (*viz.* seat pan, backrest, seat pan padding, backrest padding, lumbar support, lumbo-sacral support).

The CLMM relies on the idea that a subjective evaluation expressed on an ordinal scale (*e.g.* comfort rating) is actually a categorized version of an unobservable (latent) continuous variable.

Let Y_i the outcome category selected by subject i for the response variable. Given a set of p covariates, $x_1,..,x_k, \dots x_p$, the CLMM can be formulated as follows [17]:

$$logit\left[P\left(Y_{it} \leq j\right)\right] = u_i + \alpha_j + \beta_1 x_{1it} + \beta_2 x_{2it} + \cdots + \beta_p x_{pit} \qquad (1)$$

The parameter β_k measures the impact of x_k on Y; the parameters α_j are the category cut-points on a standardized version of the latent variable; u_i is the random effect due to subject i for response categories $j = 1, 2, \dots, J\text{-}1$; it is assumed normally distributed and centered at zero ($u_i \sim$ N $(0, {\sigma_u}^2)$).

Table 2
Seat dimensions

	Seat A	Seat B	Seat C
Height of seat [mm]	1087	1152	1136.6
Height of seat pan [mm]	435	440	453.2
Width of seat pan [mm]	424.9	424.9	457.2
Backrest configuration	Hybrid	Hybrid	Full composite
Height of backrest [mm]	707	772	780
Width of backrest [mm]	427	450	444.5
Reclining	No	Yes	Yes

Table 1
Main anthropometric characteristics of participants

	Num	Age [year] [min-max]	Weight [kg] [min-max]	Height [m] [min-max]	BMI [kg/m^2] [min-max]
Males	9	[27–41]	[73–101.8]	[1.60–1.90]	[22.8–34.7]
Mean (SD)		35 (4.4)	88(8.53)	1.77 (0.08)	28.03 (3.46)
Females	8	[26–44]	[55–75]	[1.55–1.73]	[21.15–27.55]
Mean (SD)		34 (5.9)	66 (5.4)	1.66 (0.05)	24.1 (2.08)

Table 3
Coefficients of the significant covariates for the optimal CLMM (asymptotic standard error, in parentheses)

$\hat{\beta}_{X_a}$	$\hat{\beta}_{X_l}$	$\hat{\beta}_{X_h}$	$\hat{\beta}_{X_r}$
–0.82	–1.48	0.83	2.01
(0.41)	(0.35)	(0.29)	(0.47)

The intra-class correlation (ICC) is a way to look at the correlation of observations within a group, it is calculated as follows:

$$ICC = \frac{\sigma_u^2}{\hat{\sigma}_u^2 + \sigma_u^2} \quad (2)$$

where $\hat{\sigma}_u^2$ and σ^2 represent the estimated variance of the random effect and the residual variance, respectively. Values of ICC near one indicate that observations within a group are very correlated; whereas values of ICC close to zero indicate that the random effect can be neglected since observations within a group are nearly independent [17].

4. Results

The optimal fitted CLMM for the analyzed comfort data has 4 significant covariates: *age* (X_a), *comfort feeling with lumbar support* (X_l), *height of seat pan* (X_h) and *backrest position* (X_r). The estimated coefficients of the significant covariates $\hat{\beta}_k$ are reported in Table 3 together with their asymptotic standard error.

The coefficients $\hat{\beta}_{X_a}$ and $\hat{\beta}_{X_l}$ are negative indicating that the probability of low overall comfort ratings increases with the age of the participants and the passenger feeling of a comfortable support in the lumbar area. On the contrary, the coefficients $\hat{\beta}_{X_h}$ and $\hat{\beta}_{X_r}$ are positive indicating that the probability of higher overall comfort ratings increases for seats with higher seat pan and for seats in reclined position.

The $\hat{\sigma}_u^2 = 0.003$ for the random effects model implies a low participant effect; ICC equals to 0.0009 confirms the substantial independency of comfort evaluations provided by the same participants for different seat conditions.

5. Discussion

Despite the small size of the sample, the study provides significant results. The optimal model has been identified with 4 significant covariates: two objective seat features, *height of seat pan* and *backrest position*, and two subjective covariates, *comfort feeling with lumbar support* and *age*. In the following, these findings will be compared to the field literature.

The significance of the *height of seat pan*, measured as the distance between the top of the seat pan and the floor, confirms the criticality of this parameter for the design of the seats. In a recent experimental study investigating the effects of seat parameters and sitter anthropometric dimensions on seat profile and optimal compressed seat pan surface, Peng at al. [20] found that height of seat pan was dependent on seat pan angle, stature, sitting height to stature ratio and BMI.

Some attempts have been already made to derive the optimal value of the height of the seat pan from the dimensions of the popliteal height of the end user [21]. However, it is clear that, depending on the amount of adjustability, it will be difficult to define dimensions that include the entire population. Referring to a population of passengers aged between 20 and 60 with a distribution made up of 50% of male and 50% of female passengers [22], Hiemstra-van Mastrigt concludes that a 10 mm increase in the height of the seat pan from 420 to 430 mm will include an additional 11% of passengers, but an increase of the same width, from 470 to 480 mm, will include only an additional 0.4% of passengers [21]. Therefore, a careful selection of this dimension is necessary in order to achieve an optimum trade-off between including people, increasing the comfort experience and an efficient use of space.

The significance of the *backrest position* confirms that a tilted sitting position improves passenger comfort. Several literature studies have investigated the benefits of tilted position with respect to the reduction of sitter discomfort. The tilt angle determines body posture, which is related to the interface pressure [11, 16]. Vos et al. [23] found that an increased torso–thigh angle reduced the pressure coefficient value (peak pressure, average pressure), which in turn reduces subjective discomfort. Lueder's study [24] demonstrates that a more dynamic seat, with the possibility of varying the posture adopted (for example by the reclining of the seat), reduces the perceived discomfort.

At first sight, the most surprising result of our study concerns the negative relationship between the overall seating comfort perception and the feeling of being comfortably supported at the lumbar area. The impact of the lumbar support on subjective feeling of comfort is largely unknown. The lumbar support design is usually motivated by the idea that a seat to be comfortable should preserve the curve in the low back (*i.e.* low back lordosis). It is widely understood that lumbar lordosis decreases as the angle between the trunk and hip approaches 90 percent, as in an erect sitting posture [25]. However, a recent study on office chairs has discussed a paradoxical behavior: the seat designed to ensure correct lumbar curvature recorded the highest level of discomfort and pain for the lower back by the evaluators who participated in the tests [26]. Our findings seem to confirm this paradoxical behavior and thus suggest another interesting point that deserves more research investigation.

Finally, with respect to the covariate *age,* our study evidences that the probability of low comfort rating becomes higher as the *age* of participant decreases. Despite the narrow range considered (26 to 44 years), this result seems to confirm the findings obtained in other comfort studies investigating the effect of age on (dis-)comfort perceptions.

Kyung et al. [27], in a study in the automotive field, compare the perceptions of (dis-)comfort and the pressure distribution of two groups of drivers: young (between 20 and 35 years) and elderly (with an age greater than 60 years). No significant differences between the two groups emerge in terms of overall comfort, whereas, a significant difference emerges from the point of view of local comfort assessments (*i.e.* relating to specific areas of the body analyzed during the study): younger drivers reported lower levels of local comfort than the elderly. Kyung et al. [27] also highlight that the younger drivers appeared to be more sensitive to discomfort than older drivers. A similar result emerges from a study conducted by Lijmbach et al. [28] about the aircraft seat in-and egress differences between elderly (with a mean age of 75 years) and young adults (with a mean age of 22 years). Most elderly who participated in the research were extremely positive about the comfort of the seat. This hindered the research and made it very difficult to compare the comfort evaluations provided by the two groups of participants.

Participant effect resulted negligible in our study, this finding could be related to the involvement of expert and trained assessors (*i.e.* frequent flyers) who may show less individual psychological biases in the evaluation task. However, since psychological and physiological biases generally affect the subjective assessment in a sample set, assessor's effect cannot be disregarded.

Besides the above interesting results, it is worthwhile to note that the small number of participants does not allow a generalization of the obtained results.

6. Conclusions

This paper focuses on the assessment of aircraft seating comfort based on subjective responses collected during laboratory experiments. The adopted data analysis strategy, based on CLMM, allows to investigate the strength and direction of association in subjective comfort data taking into account their ordinal nature as well as the potential grouping structure of replicated observations, overcoming the hypothesis of independency that is often unrealistic in experimental settings.

The proposed strategy is appropriate for the analysis of discomfort ratings as well. In future research, it would be interesting to investigate which factors significantly influence overall discomfort perception and also to extend the investigation by including for example the impact of aircraft vibrations on the perception of passenger (dis)comfort.

Conflict of interest

None to report.

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Statistical Modelling of Comfort Preferences and Uncertainty in Subjective Evaluations of Aircraft Seat Comfort

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Abstract. Aircraft seat is rated as the most unsatisfying aspect of flying; understanding the main factors impacting on passenger's evaluations can provide a concrete opportunity for airlines to improve seat comfort and thus enhance passenger satisfaction and loyalty. Although there is a great deal of interest, the research on effective assessment strategies for subjective comfort is still underdeveloped. In this study a model-based approach for the analysis of subjective comfort data is suggested. The model adopted can be interpreted as a parametric version of the psychological process generating comfort ratings. The proposed approach is exploited through a case study concerning comfort assessment of aircraft seats designed for regional flights.

Keywords: Aircraft seat comfort · Subjective data analysis · Laboratory experiments · Uncertainty

1 Introduction

The number of air passengers is growing and is expected to double to 8.2 billion in 2037 [1]. Contextually with this growth, there is also a growing attention towards passenger needs, service quality and comfort [2–4]. Specifically, seat comfort is an important factor for passenger satisfaction, it is related with the mode of travelling and passenger willingness to use it again. According to Hiemstra-van Mastrigt [5], "*comfortable seats can attract passengers*", since the seat is the interface of the passenger with the aircraft interior for most of the journey. For this reason, the airlines industry makes efforts to improve passenger comfort experience, in order to attract more passengers. Improving the sense of comfort associated with a trip, adopted as a measure of overall quality of the trip, results in an increase of proportion of passenger who wish to use the same airline on future occasions (*i.e.* passenger loyalty) [6, 7].

In their extensive literature review focusing on the relationships between comfort perception, anthropometry, seat characteristics and passengers activities, Hiemstra-van Mastrigt et al. [5] highlight that statistical evidence on these relationships is still lacking and emphasize the need of enhancing research on quantitative methods to properly

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investigate factors influencing passenger seating comfort so as to support seat designers and purchasers to make informed decisions.

In order to produce accurate and reliable findings, methods for the analysis of comfort data should take into account the complex nature of the subjective evaluation process. Comfort is defined as a pleasant state or relaxed feeling perceived by a human in reaction to an environment [8–10]. Comfort experiences are judged on the basis of a psychological mechanism where both preferences and uncertainty are always present and may be related to either the judge's characteristics and the environment or product features. As a consequence, the analysis of subjective comfort data should take into account both the judge's propensity for a meditated evaluation (*i.e.* based on the comfort feeling) as well as her/his propensity for a totally random one (*i.e.* uncertainty due to external circumstances such as individual comfort expectations, previous comfort experiences, state of mind). This logic characterizes the class of mixture models expressed as convex Combination of a Uniform and a shifted Binomial distribution [11–13], which have been adopted in this paper for the statistical analysis of subjective comfort evaluations of aircraft seats for economy class flights.

The remainder of the paper is organized as follows: in Sect. 2 an overview of experiments is reported; in Sect. 3 the results are fully described; in Sect. 4 a discussion of results is reported; finally, conclusions are summarized in Sect. 5.

2 Overview of Experiments

A total of 28 volunteers (14 females and 14 males; aged between 24 and 44 years) have been selected to participate in the aircraft seat comfort experiment using the following criteria:

(1) to be free from severe musculoskeletal disorders in the last year;
(2) to have taken at least 2 flights in the last year;
(3) to be economy class flyers.

Procedures for participant recruitment and data collection have been defined taking into account ethical considerations. Before providing the informed consent, participants have been briefed about type, number and duration (40 min) of each comfort trial, as well as on research aims and treatment of the collected data. The selected group of participants is representative of the anthropometric variability in the Italian adult population with respect to both weight and height [14]. The main anthropometric measures are listed in Table 1.

The comfort experiments took place in a laboratory environment equipped with two rows of aircraft double-seats. Each participant sat in a fixed posture in a seat of the second row with a pitch of 32 inches that realistically replicate legroom. Each participant was involved in 5 test sessions to evaluate the comfort of 3 aircraft seats. The seats differed in terms of weight, reclining, dimensions of seat pan and backrest. Specifically, participants assessed the comfort of 2 typical double-seats identified as "baseline configurations" (hereafter denoted seat A and seat B) and 1 lightweight double-seat (hereafter denoted C; confidential). Seat A, being not reclining, was tested only in upright position while

Table 1. Main anthropometric characteristics of the participants

	Num	Age [year] [min-max]	Weight [kg] [min-max]	Height [m] [min-max]	BMI [kg/m^2] [min-max]
Males	14	[27–41]	[69–100]	[1.60–1.90]	[22.8–34.7]
Mean (SD)		36 (4.1)	85.1 (10.10)	1.78 (0.07)	28.6 (3.29)
Females	14	[26–44]	[44.8–83]	[1.53–1.74]	[21.5–27.5]
Mean (SD)		34 (5)	67.2 (10.3)	1.66 (0.06)	24.8 (2.10)

seat B and seat C were tested both in upright and reclined position. Each participant tested the 5 seats configurations following a crossover design in order to guarantee repeatable and homogeneous test conditions and minimize the impact of well-known noise factors like day of the week, testing order and inter-individual variability [15].

In each test session, a trained interviewer asked the participant to express her/his overall seat comfort perception as well as her/his perception related to the comfort of specific seat features.

2.1 Statistical Data Analysis

Seating comfort evaluation can be assumed as the result of a complex subjective decision influenced by two main components: the subject *feeling* towards the evaluated seat and the *uncertainty* surrounding the final choice due to external circumstances like the subject comfort expectations and her/his state of mind at the moment the evaluation is provided.

Starting from this premise, the collected subjective seat comfort evaluations have been modelled as a Combination of a Uniform distribution and a shifted Binomial distribution [11–13]. The Binomial distribution is intended to model the propensity to adhere to a meditated evaluation interpreted as the result of a counting process within a sequential selection among the *m* ordered judgment categories, whereas the Uniform distribution is introduced as the most unpredictable case among all discrete alternatives to mimic a pure random choice. The adopted CUB model will be hereafter briefly described following the multi-product framework proposed in Capecchi et al. [16].

Let $\mathbf{x_i^{(\pi)}}$ and $\mathbf{x_i^{(\xi)}}$ be the covariate vectors explaining the uncertainty and feeling component, respectively, for subject *i,* with *i* = *1,..,n*, and let H be the vector of measurements available for each product (*i.e.* seat) *k,* for *k* = *1,…,K*.

A CUB model for the ordinal response *R* is specified by:

$$\Pr\left(R = r \middle| \mathbf{x_i^{(\pi)}}; \mathbf{x_i^{(\xi)}}; \mathbf{z_k}\right) = \pi_{ik}\binom{m-1}{r-1}\xi_{ik}^{m-r}(1-\xi_{ik})^{r-1} + (1-\pi_{ik})\frac{1}{m} \quad (1)$$

for *r* = *1,…,m; i* = *1,..,n; k* = *1,…,K.*

The subject and product covariates are linked to the CUB model parameters (π, ξ) as follows:

$$\begin{cases} \pi_{ik} = \frac{1}{1+e^{(-\mathbf{x_i^{(\pi)}}\beta - \mathbf{z_k}\delta)}} \\ \xi_{ik} = \frac{1}{1+e^{(-\mathbf{x_i^{(\xi)}}\gamma - \mathbf{z_k}\eta)}} \end{cases} \quad (2)$$

for $i = 1,..,n$ and $k = 1,\ldots,K$, being $(\boldsymbol{\beta}, \boldsymbol{\gamma})$ and $(\boldsymbol{\delta}, \boldsymbol{\eta})$ the parameter vectors measuring the impact of subject and product covariates on uncertainty and feeling components, respectively.

It should be noted that the intercepts β_0 and γ_0 in (2) represent the joint level effect of *i*-th subject and *k*-th product with regard to the CUB components.

3 Results

Coherently with the adopted framework for the analysis of subjective comfort responses, the seat comfort evaluations collected during the laboratory experiments have been arranged in the following three matrices:

- matrix R [5, 28] containing the subjective overall comfort ratings provided by the 28 participants for the 5 seat conditions under study;
- matrix X [28, 3] containing 3 anthropometrical characteristics for the 28 participants: age (x_1), gender (x_2) and BMI (x_3);
- matrix Z [5, 15] including 8 physical attributes and 7 comfort attributes distinguishing the 5 aircraft seats. The physical attributes are height of seat (z_1); height of seat pan (z_2); depth of seat pan (z_3); width of seat pan (z_4); backrest configurations (z_5); height of backrest (z_6); width of backrest (z_7) and backrest reclining (z_8). The comfort attributes are comfort of seat pan padding (z_9); comfort of seat pan at buttocks (z_{10}); comfort of seat pan at back of thighs (z_{11}); comfort of seat pan behind the knees (z_{12}); comfort of backrest padding (z_{13}); comfort of backrest support (z_{14}) and comfort of lumbar support (z_{15}).

The coefficient estimates for the CUB model fitted for aircraft seat comfort evaluations are reported in Table 2.

Table 2. Parameters estimates (standard errors) for the CUB model.

$1 - \pi_{ik} = 1 - \pi$	$\log it(1 - \xi_{ik}) = \gamma_0 - \eta_2 z_2 - \eta_{13} z_{13}$		
$1 - \pi$ 0.121 (0.053)	γ_0 3.645 (0.850)	η_2 −0.715 (0.144)	η_{15} 0.374 (0.083)

The results provide evidence of low uncertainty in comfort responses ($1 - \pi_{ik} = 0.121$); the comfort of lumbar support has a significant positive effect over the comfort responses ($\eta_{15} = 0.374$) whereas the height of seat pan ($\eta_2 = -0.715$) produces a negative effect.

4 Discussion

The estimated model shows that the uncertainty does not play an important role in the evaluation process, this result may be explained by the characteristics of the participants involved in the comfort experiments: they are all frequent flyers, fully engaged in the evaluation process and trained for the evaluation task.

The estimated model reveals that the seating comfort is positively influenced by the comfort of lumbar support and negatively influenced by the seat pan height.

As already emerged from previous research studies [17], the significance of the comfort of lumbar support draws attention to this seat parameter, which has been much investigated from the technical point of view but whose impact on subjective feeling of comfort is largely unknown [18, 19]. The lumbar support design is usually motivated by the idea that a seat to be comfortable should preserve the curve in the low back (*i.e.* low back lordosis). It is widely understood that lumbar lordosis decreases as the angle between the trunk and hip approaches 90%, as in an erect sitting posture [18]. However, a lumbar support designed in this way is not always perceived as comfortable as discussed in a recent study on office chairs that evidences a paradoxical behavior: the seat designed to ensure correct lumbar curvature recorded the highest level of discomfort and pain for the lower back by the evaluators who participated in the tests [19].

The seat pan height, measured as the distance between the top of the seat pan and the floor, is one of the most critical parameters for seat design [20] and a careful selection of this dimension is necessary in order to achieve an optimum trade-off between including people, increasing comfort experience and an efficient use of the space; it is the subject of several researches to derive the optimal value considering the dimensions of the popliteal height of the potential passenger [20]. It is clear that, depending on the amount of adjustability, it will be difficult to define dimensions that include the entire passenger population comfortably.

5 Conclusions

The strategy here proposed for analyzing comfort data seems helpful to produce evidence in order to identify critical factors to improve seat design. The main advantages of the proposed approach are the following: (1) it explicitly takes into account the subjective nature of comfort data; (2) it separates the role of expressed preferences from that of uncertainty; (3) it allows to study the effect of passenger and seat covariates on the liking patterns in a multi-product setting.

A critical issue of the study is the moderate sample size, it is likely that with a larger sample of potential passengers, more meaningful relationships could be derived. However, the investigated sample size is very common in laboratory experiments and the adopted approach revealed effective even in these conditions.

Finally, in future research, it would be interesting to investigate which physical seat factors significantly influence the overall discomfort perception and also to extend the investigation from a dynamic perspective, *e.g.* including the impact of aircraft vibration on passengers (dis-)comfort subjective analysis.

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Towards a hybrid comfortable passenger cabin interior for the flying V aircraft

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Towards a hybrid comfortable passenger cabin interior for the flying V aircraft

Cover Page Footnote

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A new type of long-haul aircraft, ‘the Flying V’ is in development, which consumes less energy by its form (https://www.tudelft.nl/lr/flying-v/). Air transport currently accounts for around 2% of the 36 billion tonnes of CO_2 generated annually by human activities (https://www.cleansky.eu/benefits), showing the need to develop a more fuel-efficient aircraft. This Flying V is originally an idea of TU Berlin student Justus Benad during his thesis project at Airbus Hamburg (https://www.tudelft.nl/lr/flying-v/). In the Flying V, the passenger cabin, cargo hold and fuel tanks are integrated in its wing structure. The Flying V carries about the same number of passengers as the Airbus A350, which is the benchmark for this new airplane. The Flying V is smaller than the A350 and has less wetted surface area compared to the available amount of volume. The result is less resistance, which causes less fuel need for the same distance. At the moment the Flying V is in development for using traditional kerosene engines, but also alternative ways of propulsion will be studied like hydrogen or e-kerosene, but this is not the purpose of this study.

The Flying V does not consist of a traditionally configured circular fuselage with a set of wings, but rather integrates the cabin into the wing itself. The resulting cabin has a flat oval cross section which would deform to circular when pressurized at high altitudes. In order to prevent this, a rectangular frame is positioned in the oval cabin (Vos, Geuskens, & Hoogreef, 2012). In fact, the inside space of the rectangular is the space where seats can be placed (6.00 m x 2.15 m). This shape asks for new interior concepts.

The development of new interior concepts is not only driven by the shape of the flying V but also by the passenger’s comfort. Passenger comfort is clearly a key variable in research on user acceptance of transportation systems, and it is related to passenger’s satisfaction and the willingness to fly again (Li, Chu, Gou, & Wang, 2018). Anjani, Li, Vink, and Ruiter (2019), and Bouwens, Tsay, and Vink (2018) have shown the need to improve seating: seat comfort has been seen as a necessity rather than a luxury. According to a study conducted by Airbus, long-haul economy passengers take great care over seat comfort in long flights, and they are willing to pay more for this. In the study, 54% of economy passengers stated that seat comfort was essential, while 41% of the passengers stated that they were willing to pay more for better seat comfort (Atalık, Bakır, & Akan, 2019). Kremser, Guenzkofer, Sedlmeier, Sabbah, and Bengler (2012) and Hiemstra-van Mastrigt (2015) demonstrated the need to change postures as a passenger. Furthermore, the possibility to change one’s posture easily could lead to the effect that passengers do not sit too static on an airplane and perform different activities. Sleeping is one of the common activities during the long haul flight: Bouwens, Hiemstra-van Mastrigt, and Vink (2017) showed that almost 80% of the passengers sleep, but due to the upright posture the comfort is rated low (4.3 at a scale of 1-10); Torkashvand (2019) showed that on long haul flights the lowest satisfaction was found for the activity ‘sleeping’ (the score is 2.75 on a scale 1-5, where from 1=“not at all satisfied” and 5= “extremely satisfied”). So, there is also a need to improve the passenger experience by creating new interior concepts that can answer to the different passenger needs. Therefore, in this paper an attempt is made to develop aircraft interior concepts that fit in the Flying V and could improve the passenger experience.

A requirement was that, for a given floor area, the interior should have space for 315 passengers comparable to the Airbus A350. An additional requirement was that the weight of the new interior elements should be lower than the current interior elements to reduce energy consumption even further.

Method

To develop concepts for the interior of the Flying V, 80 students were asked to come up with ideas in groups of 3-4 (22 groups). Before generating ideas, the students were informed about the Flying V concept and its oval cabin (including dimensions). The number of passengers that had to fit in the airplane was explained as well. Also, improvement possibilities based on current surveys among passengers were mentioned, such as the need for more space, more variation of posture, the need for sleeping comfortably, that 28% of the passengers travel in groups (Homburg, 2017), that talking to each could distract of discomfort (Hiemstra-van Mastrigt, 2015), and food could distract from discomfort (Hiemstra-van Mastrigt, 2015; Yao & Vink, 2019).

The 22 groups of students were also sensitized and received a lecture on aircraft interiors in a Boeing 737 to experience aircraft interiors again. Each group presented one or more ideas and a jury of experts from KLM (an airline), Safran (a company making airplane interior parts), Airbus, and TU-Delft selected the best 4 ideas. The groups that had the ideas did receive a student-assistant appointment. In that appointment, they were asked to further elaborate the concept and make it into a drawing which can be made.

Simultaneously, the researchers developed a 1:1 mock-up (see Figure 1) and a stand builder was asked to make the mock-up frame and a part of the interior. A seat manufacturer (Rebel aero) was asked to develop seats that were positioned staggered as was suggested in the ideas of the students. Also, a design language was developed to create unity in the interior design. The method of generative design was chosen here as it could contribute to less weight and at the same time have recognisable design elements. The four concepts in the mock-up were shown to the public (potential passengers) at the fair where KLM 100 years was celebrated during 9 days.

Figure 1. The Flying V (left) and the mock-up of the interior of the Flying V (right).

At the beginning of the visit, two tickets were provided to each visitor to allow him/her to express his/her preference on the concepts presented in the mock-up. The preferences are asked under two travel conditions: when he/she travels alone or when he/she travels in a group (at least 2). The visitors provided their preferences at the end of the visit, inserting his/her preference in one of the four boxes that represented the four interior concepts shown in the mock-up.

Additionally, the concepts were discussed with most of these visitors. In the discussion it was explained that during a flight, passengers could book for instance a bed for the first half and a staggered seat for the second half of the flight, suggesting a new way of booking the flight.

Results

The four chosen concepts were the chaise longue (see Figure 2), the group space (see Figure 3), the beds (see Figure 4), and the ‘staggered’ seats for the middle of the Flying V interior (see Figure 5).

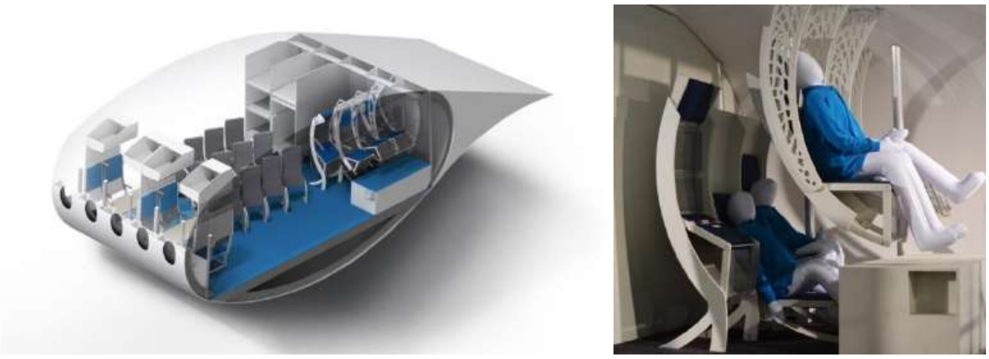

Figure. 2. A schematic overview of the mock-up (left) and one of the concepts for the interior of the Flying V: the chaise longue (right).

Figure 3. One of the concepts for the interior of the Flying V: the group space.

Figure 4. One of the concepts for the interior of the Flying V: the beds.

Figure 5. One of the concepts for the interior of the Flying V: the staggered middle seats.

In the chaise longue concept, it is possible to change the position of the human body. There is a more upright position for eating and working with the laptop and a more reclined position for relaxing and sleeping. It uses the available space in the aircraft by hanging the top seats from the ceiling. As the cabin is oval, and the ceiling consists of horizontal beams, mounting is possible. There is a rail in which the seat moves to different positions. Three seats are mounted to the floor and three to the ceiling. The ones mounted to the ceiling have a foot step to get into the seats. This way two rows of seats take up the same floor space of 64” (2 x 32” pitch), but allow more variation of posture for the passengers. There are three positions: a position for passing each other during ingress and egress (most left seat in Figure 2) and the other two positions (upright and relaxed).

In the group space, two pairs of seats are position opposite to each other with a table in between. To allow ingress and egress a part of the table is made foldable. Also, between both seats a separation between the heads can be pulled out of the backrest at head level. This is to create some privacy when two groups of two are in the seats. The lower part of the backrest is a net, which stretches a bit and the form of the back rest is based on the curve described by Nijholt et al. (2016). These four seats (2x2) could take up less than 64” of space in the cabin’s longitudinal direction, as it is assumed that the knees of two persons opposite to each other can touch each other as these persons are acquaintances. For the same reason, and because the group seats are designed as 2-seaters, the total width could also be smaller than the total width of 2 separate seats. The additional space between the rectangular frame and the oval cabin wall provides more visual space, some shoulder space and the possibility to put some personal belongings.

In the concept beds, it is possible to sleep in a flat bed. The original rectangular frames to keep the oval cabin oval at high altitudes were positioned 50 cm from each other. However, as we wanted to have beds in between the rectangular frames, 70 cm would be better and a redesign was made of the frame structure in the oval cabin. The 70 cm frame distance makes it possible to position the beds between the frames and use the space in the posterior part of the wing. This way a 190 cm long bed only uses 140 cm of the length of the area within the rectangular frame. It is not allowed to lay flat during take-off and landing. Evacuation will take too much time. To prevent losing capacity in the number of passengers, a part of the bed area had to made transformable to a seat. The solution developed was to lift the middle bed up and let a part of the lower bed flip down from horizontal to vertical and to create for three persons a seat. In Figure 4, the left three beds are in a sleeping position and the right three beds in a sitting position.

The middle seats are placed in the direction of flying with a seat pitch (in the longitudinal cabin direction) of 32”. These seats were 18” wide, placed four abreast in a staggered position. As the wing has an angle of 26 degrees with respect to the direction of flying, the seats have an angle of 26 degrees with respect to the oval tube. To make ingress and egress possible the seat pan can be folded, a principle designed by Rebel Aero (see Figure 6). This also has the advantage that passengers can temporarily take another position on the folded seat. Another advantage of the staggered seats it that shoulders and the elbows at the armrests are not touching each other easily. By rotating the seats, the leg room was comparable to a 38” pitch.

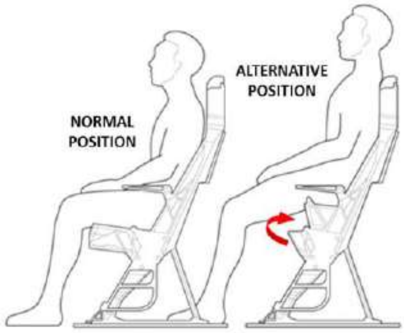

Figure 6. The principle of the folded aircraft seat developed by Rebel Aero.

The Visitor Comments

A total of 1692 visitors of the mock-up provided their preference for one the four concepts. The sample of visitors (potential passengers) was very heterogeneous. The majority were middle-aged, but also young visitors of 10 years old and elderly of more than 70 years old visited the booth. They had to give their preference when they fly alone and when they fly in a group of at least 2. In Figure 7, the preferences of the 1692 visitors of the Flying V are shown. It makes sense that there is a preference for the group seats when travelling in groups. However, it was a surprise that the chaise longue was the favourite for individual travelling and even for travelling in groups there were many votes for this seat.

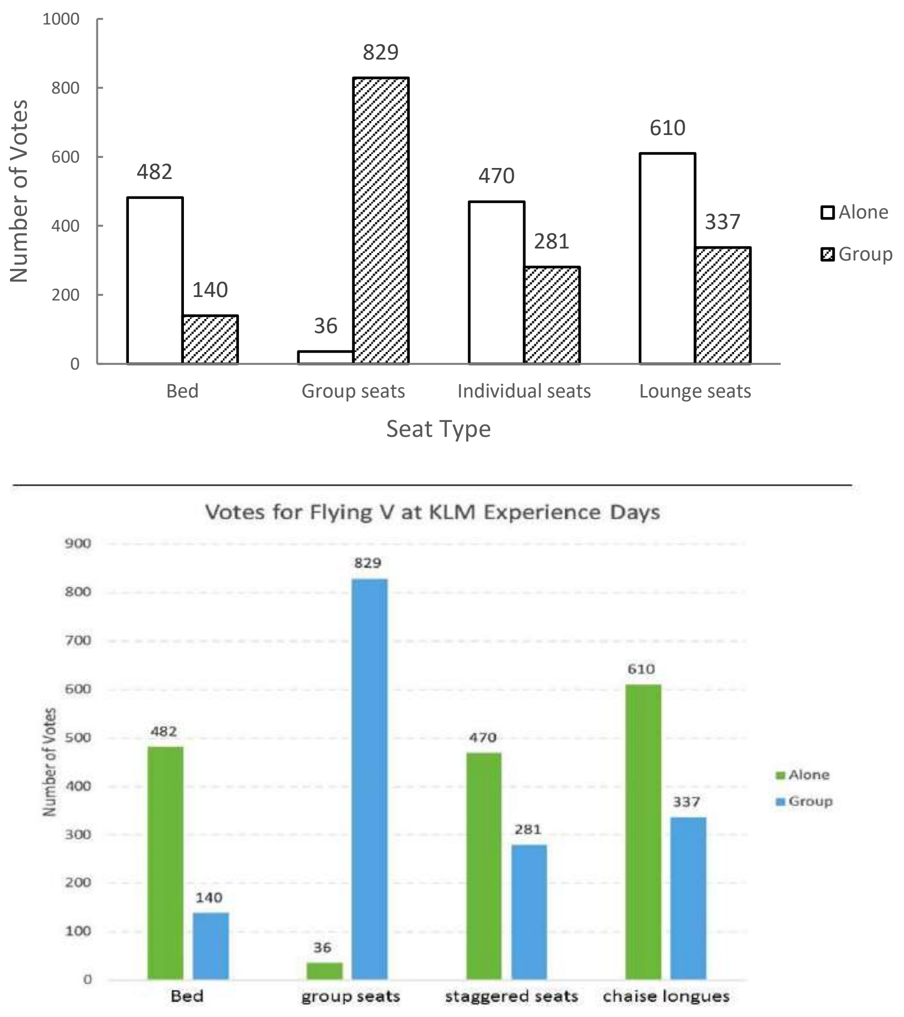

Figure 7. Votes of the 1692 visitors for the concept.

In the discussions the flight attendants mentioned that changing half way during the long-haul flight might be a problem. If everyone changes at the same time, it will be uneasy. Perhaps this should be regulated and be done in groups at different times.

The group space was seen as interesting and reminded the visitors of train seats. They did mention as well that 12 hours in this position is too much. Planners of an airline said that it might be true that on average 28% travel in groups, but less group spaces should be made in the airplane as there will be flights with only 10% groups and then these places will not be booked, which is unfavourable for an airline. So, preferably less than 28% should be group space.

The chaise longue was really appreciated as the human body position can be changed. Notably, the relax position was seen as a benefit. The demonstrated seat was not fully functional, which means that the visitors could only visually inspect the situation and not sit in it. Some visitors mentioned that it could be a claustrophobic experience when the lower person is sitting upright and the person above will recline.

The flat bed was also appreciated, as sleeping is really an issue now, but being in the bed for the full 12 hours is not preferred according to some visitors. Also eating in this position might be an issue. Perhaps also at eating time the taxi, take-off and landing position should be taken. Getting in and out of the bed and changing the sheets during the flight should be tested as well as there were some doubts about this by the visitors. A suggestion was made to give every passenger that will sleep his own sheet and cushion to give the passenger certainty on the hygiene. Especially, elderly getting in and out of the highest bed could be troublesome.

Figure 8. The staggered middle seats of Rebel Aero in the flying V showing that shoulders do not contact each other and elbows are at a different place on the armrest.

It was also clear that the staggered seats were appreciated above the conventional seat configuration, because of the shoulder space, armrest privacy and legroom. The shoulders do not touch each other (see Figure 8) and the elbows are at the armrest in a position that does not conflict with the neighbour. A disadvantage might be privacy as the person positioned just a bit behind the other could watch the screen of the laptop or smartphone of their neighbour more easily than in the current situation. Also, the fact one of the four passengers will put the legs in the aisle could be an issue. Although some flight attendants mentioned that it happens now as well that passengers put their legs in the aisle. Some passengers also mentioned that the armrest and area under the armrest of the seat in front of the passenger contacting the knee could be redesigned to create space and the seat pan cushions should be softer for long haul flights. Next to the seat softness visitors also mentioned that the backrest angle should be more backwards or an addition of a recliner would be beneficial. However, the latter will introduce some extra eight, while the seats now are lighter than the current flying seats.

Also, some visitors (experts in the field of aircraft interiors) mentioned that sitting with an angle of more than 18 degrees from the direction of flying needs additional measures as crashes will be worse for the human body. Extra measures could be needed like airbags. They pointed to literature on obliquely oriented seats (Humm et al., 2016). Some visitors also mentioned that booking for half of a flight and changing the seat is certainly appreciated. However, the practicality of the booking and changing needs further research. Another issue that was mentioned is evacuation. Having only exits on one side of the oval cabin might make the evacuation much harder. It still remains unknown to what extent, and how specifically, current regulations should fit this unconventional aircraft design.

Discussion

The first steps toward developing aircraft interior concepts that fit in the Flying V and could improve the passenger experience are made and it seems that all ideas get some support. Especially, the chaise longue is appreciated. However, a lot has to be studied further. In general, the evacuation needs further study, but also the booking and being seated more than 18 degrees off the direction of flying (according to studies like Humm et al. (2016) need further research. The latter might mean airbags for the sitting position in the bed, for the group space and chaise longue. Booking for half a flight might be an issue at a system level, as for instance the current booking systems don’t have that option. But also in the daily practice of flying, attention is needed on how the passengers move and how to plan it in the flight schedule. For the specific four ideas, further research is needed.

Regarding the chaise longue, it is seen as promising by visitors as was mentioned before. Also, the use of the space in vertical direction to create more seat positions has been done before (e.g. http://jacob-innovations.com/FlexSeat.html and the Crystal Cabin Award winners 2019: Visionary Concepts ULTRAFLEX by AIM and the Boeing Company). So, many see this opportunity. However, in realizing it further steps still have to be made as all these concepts do not function yet and do not fly. Therefore, for the chaise longue, it is important to make a functional seat, with a mechanism to mount it to the fuselage, a working mechanism making the movement and then test it again with passengers.

In addition, the group space is not new. For instance, Rockwell made this set up for business jets (https://www.rockwellcollins.com/Products-and-Services/Business-Aviation/Cabin-Interiors/Seating-Products/Executive-and-VIP-Seating.aspx). Also, in trains it is often seen. However, in regular airliners this seat is not found yet. The safety certainly needs further study especially for the seat with the table in front of the passenger in the flight direction. Also, sitting in this position all the time in a long-haul flight might be too long and solutions are needed for that. Piro et al., (2019) showed that sitting opposite to each other is not the most comfortable position regarding communication. A 45- or 90-degrees position is more desirable for communication.

For the beds, duration might be an issue. Being in the bed 12 hours is seen as too long by the visitors. However, the flat bed is promising. Around 70% of the humans sleep on the side (Gordon, Grimmer, & Trott, 2007) and this flatbed allows this position. Also, Torkashvand (2019) showed that among long haul flight passengers (95% economy class) the lowest satisfaction was found for the activity ‘sleeping’, while sitting upright. This was affirmed by a survey among flight attendants in the same study. The mechanism for changing the beds to the seats for taxi, take-off and landing still has to be developed further. The interesting part of this development is that it might fit in current planes as well. Of course, going into the oval end of the cabin is not possible in traditional airplanes.

The staggered seats seem a good solution. It was appreciated and visitors preferred this over the current economy class seats on long haul flights, because of the leg space, not contacting the shoulder of the neighbour and not having to fight for the armrest. However some adaptations have to be made (e.g. cushion hardness, back rest inclination, the knee space at the arm rest in the seat in front of the passenger and it might be interesting to see if the 32” pitch can be reduced as leg space is now comparable to a 38” pitch, which seems a lot. Anjani et al. (2019) showed that 34” is already experienced as convenient. So, this should be studied further as well.

Conclusion

The hybrid interior of the flying V having a flat bed, staggered seats, a group space and a chaise longue, where different postures can be taken is appreciated by potential passengers. It is also clear that still much has to be studied further, like changing from one seat to the bed in the middle of the flight, evacuation and more detailed designs will be needed. The chaise longue seat certainly has potential as it is most preferred by the visitors.

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A Staggered Seat is Beneficial for the Flying V Aircraft

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Abstract. Staggered seats might be a solution for a V-shaped aircraft (the Flying V). The cabin longitudinal axis of this airplane has a 26° angle with respect to the direction of flight. When seats are positioned in the direction of flight, they consequently have an angle to the cabin and become staggered. It is unknown whether the comfort of this staggered seat is appreciated. In this study, 117 participants tested the comfort and the privacy experience in this staggered seat compared with a regular aircraft seat. The experiment showed that both comfort and privacy were significantly better in the staggered seats. However, the analysis is based on short-term evaluations, which means that long-term effects still need to be studied and also the effects of groups travelling together need to be investigated.

Keywords: Aircraft seat · Staggered · Comfort · Flying V · Leg room · Arm Rest

1 Introduction

1.1 A New Aircraft: The Flying V

Flying V is a new type of long-haul aircraft under development (Fig. 1), whose form will allow a reduction of 20% in energy consumption due to its unique shape (Vink et al. 2020). The Flying V does not consist of a traditionally configured circular fuselage with a set of wings, but the passenger cabin, cargo hold and fuel tanks are integrated in the wing structure of the Flying V. At the moment, the Flying V is designed to use traditional kerosene engines, but also carbon neutral ways of propulsion, like hydrogen or synthetic kerosene, are under study.

1.2 Staggered Seats

The wings of the Flying V have an angle of 26° with respect to the direction of flight, which means that the cabin (integrated in the wing structure) has this angle as well. As a consequence traditional seats placed in the direction of the cabin, would also have such an angle with respect to the direction of flight. Because of crashworthiness,

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Fig. 1. An impression of the Flying V that is under development.

safety regulations do not allow an angle of more than 18° from the direction of flight (Humm et al. 2016), for this reason, a staggered seat placed in the direction of flying was considered for the Flying V. This means that the seat has an angle of 26° with respect to the cabin and the adjacent seat closer to the center of the airplane is slightly set back (Fig. 2); the front of the seat can be flipped up to enable in- and egress (Fig. 3).

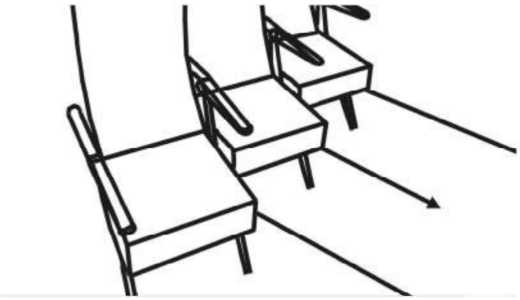

Fig. 2. Staggered seats of the Flying V. The arrow is the direction of the cabin in the wing and the seats are in the direction of flight and angled with respect to the cabin.

Fig. 3. To allow in- and egress and variation in posture the seat has the possibility of flipping up the front part of the seat.

The Rebel company had these seats available and adapted them for the Flying V. A 1:1 mock-up (6 m wide, 2.1 m high and 6 m long) of a cross section of the Flying V cabin was made and two rows of four staggered seats were placed in it.

Moving from the idea that the understanding of passenger comfort experience and its implications for the design of the aircraft interior is becoming a competitive edge in the aerospace industry, the research question is to investigate how Flying V staggered seats are perceived from potential passengers in terms of comfort. The comfort analysis includes also an investigation on the experience of privacy and control when potential passengers are seated in the aircraft, because this is an important factor in determining the overall comfort experience (Ahmadpour et al. 2016).

2 Overview of Comfort Study

An explorative study, involving 117 participants, was carried out to investigate the seating experience of new staggered seats (the Flying V seats) compared with regular aircraft seats, in terms of comfort and privacy. All participants tested in a random order both seats in the same conditions. In the first comfort test, each participant sat in the second row of the tested seats (regular or staggered); for the first 5 min the participant was free to choose to perform an activity (i.e. reading a magazine, talking to their neighbor or using his/her smart phone); in the last 5 min, he/she had to complete an online questionnaire with his/her mobile phone. The online questionnaire was accessible by scanning a QR code located at the back of the seat in front of the participant.

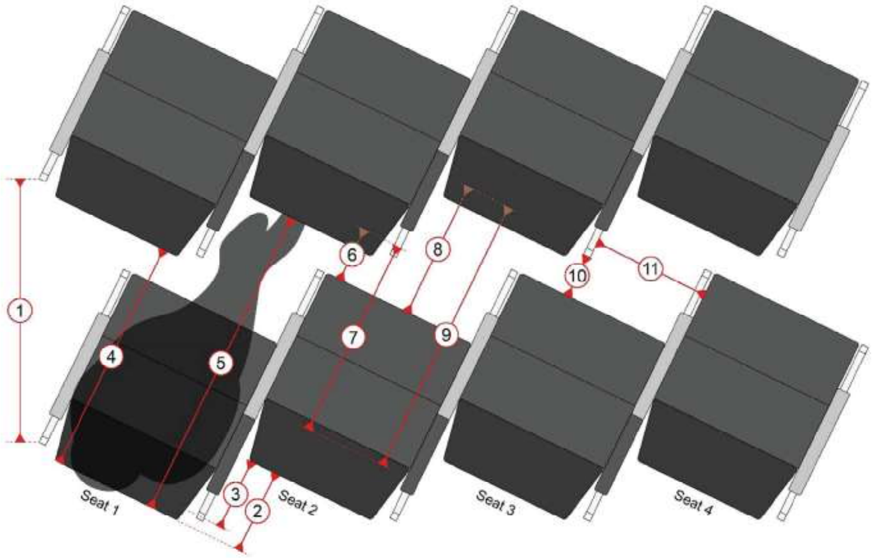

Fig. 4. Top view of the dimensions of the staggered seats. 1 = 79 cm (31″ pitch); 2 = 24 cm; 3 = 18 cm; 4 = 71 cm; 5 = 94 cm; 6 = 27 cm; 7 = 68 cm; 8 = 52 cm; 9 = 92 cm; 10 = 17 cm; 11 = 31 cm.

At the end of the first comfort test, participant moved to the other seat to be tested (e.g. the regular if he/she had tested the staggered and vice-versa), he/she repeated the comfort test, by performing the same activity and then completed the questionnaire.

The two seats analyzed were positioned at 31″ pitch, the regular aircraft seats were 18″ wide, the staggered ones were 17.8″ wide. It is worth pointing out that, the pitch of these seats is not comparable (Fig. 4 and Fig. 5) due to the 26° angle with respect to the flying direction of Flying V. Participants rated the overall seat comfort as well as the comfort of specific seat features using a 10-point Likert scale (1 = no comfort; 10 = extreme comfort) and the same scale was adopted to rate his/her privacy experience (1 = no privacy; 10 = extreme privacy).

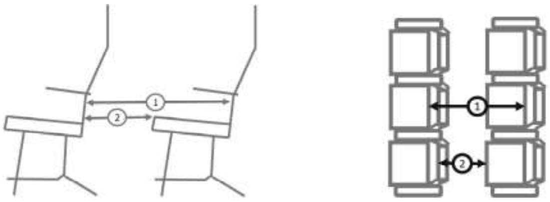

Fig. 5. Dimensions of the regular aircraft seat. 1 = 79 cm (31″ pitch); 2 = 35 cm.

2.1 Statistical Data Analysis

Data analysis was aimed at comparing the comfort and privacy experienced by participants when testing the regular seat and the staggered seat. The Wilcoxon signed rank test was applied to assess the significance of differences in perceived comfort between the two seats under study.

A cumulative logit model (CLM; McCullagh 1980) was applied in order to investigate whether differences in overall comfort ratings could be related to passenger characteristics and/or seat comfort features. The CLM is probably one of the most well-known regression models for ordinal data (Agresti 2010) and it can be properly adopted to model subjective comfort data that fall in an ordered finite set of categories.

3 Results

The main anthropometric characteristics of the 117 participants involved in the study are reported in Table 1.

For both staggered and regular seat, the median comfort score was 7 and the median absolute deviation (MAD) was 1. The Wilcoxon signed rank test did not show a significant difference in overall comfort between the staggered and regular seat, nevertheless the scores obtained by the staggered seat were significantly higher than the ones obtained by the regular seat for the comfort of the armrest ($pvalue = 5.33 \cdot 10^{-7}$), the comfort of the seat pan behind the knees ($pvalue = 0.013$) and the comfort at the upper part of the backrest ($pvalue = 0.012$). For the question ‘do you have enough privacy?’ (1 = no privacy; 10 = extreme privacy), the staggered seat obtained scores that were significantly

Table 1. Main anthropometric characteristics in terms of mean, (standard deviation), [min -max].

	Num	Age [years]	Height [cm]	Weight [kg]
Female	58	30 (18.17) [11–70]	166.4 (22.2) [153–184]	65.4 (12.3) [36–94]
Male	59	33.7 (18.6) [11–71]	180.5 (10.8) [146–205]	75.3 (14.9) [38–116]

higher ($pvalue = 0.0045$) than the regular seat with median scores equal to 6 (MAD = 2) and 5 (MAD = 2), respectively.

The explanatory variables included in the two CLMs fitted to explain the overall comfort of the two seats under study are 4 anthropometrical descriptors (age, x_1; gender, x_2; height, x_3; weight, x_4) and 5 specific seat comfort features (comfort of the armrest, x_5; comfort of the backrest in the upper part, x_6; comfort of the backrest in the lower part, x_7; comfort of seat pan, x_8; comfort of seat pan behind the knees, x_9). In order to improve model interpretability, the 5 variables related to specific seat comfort features were transformed into dichotomous variables taking the value 7 as a cut-off point for assuming a good comfort perception. The estimates for the CLM parameters are reported in Table 2.

Table 2. Significant CLM parameters for staggered and regular seat.

Staggered seat				Regular seat			
Parameter	Estimate	Standard error	p-value	Parameter	Estimate	Standard error	p-value
$ß_2$	1.17	0.344	0.0006	$ß_6$	0.77	0.407	0.06
$ß_9$	0.659	0.339	0.052	$ß_7$	1.083	0.406	0.008

The significant variables are not the same in the two models: gender (x_2) and perceived comfort of the seat pan behind the knees (x_9) were significant for the staggered seat; whereas perceived comfort in the upper and lower part of the backrest (x_6, x_7) were significant for the regular seat.

Interpretation of the CLM parameter estimates by odds ratios provides interesting information. For the staggered seat, a high overall comfort evaluation is 3.2 times more likely for female participants than for males; participants with a good comfort perception of the seat pan behind knees are 1.9 times more likely to assign higher overall seat comfort score. For the regular seat, participants with a good comfort perception at the upper and lower part of the backrest are respectively 2.2 and 3 times more likely to assign a higher overall seat comfort score.

4 Discussion

The staggered aircraft seats of the Flying V that fulfill safety regulations seem promising. The comfort and privacy experience are both evaluated better. Probably the fact that each passenger has its own space on the armrest and the fact that there is more shoulder space because the shoulders are not exactly next to each other (Fig. 6) contributes to the positive comfort experience. This influence was affirmed in a previous study (Vink et al. 2020), though in that study participants mentioned more complaints like that the seat was hard and that the backrest angle should be more backwards. Some participants also mentioned that the arm rest is of hard plastic.

The comfort score for the regular seat in this study is comparable to the results of the study of Anjani et al. (2020), who reported around 6 for 30″ pitch and around 7 for a 32″ pitch. The comfort score for the staggered seats in this study was 7, while in another study it was 7.9 (Liu et al. 2021) with the same staggered seat. However, in that study there were not always neighbors, which might indicate the importance of privacy. Torkashvand et al. (2019) showed that in a conventional configuration, the middle seat is the least preferred one, because of the contact to neighbors, however, passengers that travel in groups like to have seats next to each other and they do not bother about the shoulder contact. So, probably for groups this seat might not be ideal, but this issue needs to be further investigated.

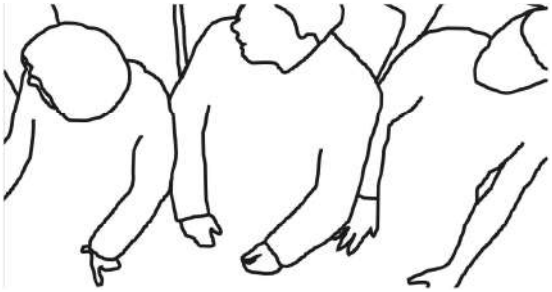

Fig. 6. In the staggered seat there is no shoulder contact and there is a separate space at the armrest.

An important limitation of this study and the previous study on staggered seats (Liu et al. 2021) is that the participants tested the seat for only 10 min. Smulders et al. (2016), Li et al. (2017) and Vanacore et al. (2019) show that discomfort increases over time. Therefore, long term tests are needed in order to confirm whether the observed effects hold for a 6–12 h flight.

5 Conclusion

A staggered seat was tested for a new aircraft configuration where passengers are positioned in the wing. The longitudinal axis of the cabin inside the wing has an angle of 26° with respect to the flight direction. The seats were placed in the direction of flight, which means that they had an angle towards the cabin and the adjacent seat closer to the middle of the airplane is slightly shifted backwards. This staggered position has the advantage that shoulders do not touch each other and arms have a separate spot at the arm rest. This study showed that the participants experiencing both this staggered seats and regular seats rated comfort for specific seat features and privacy of the staggered seats higher.

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